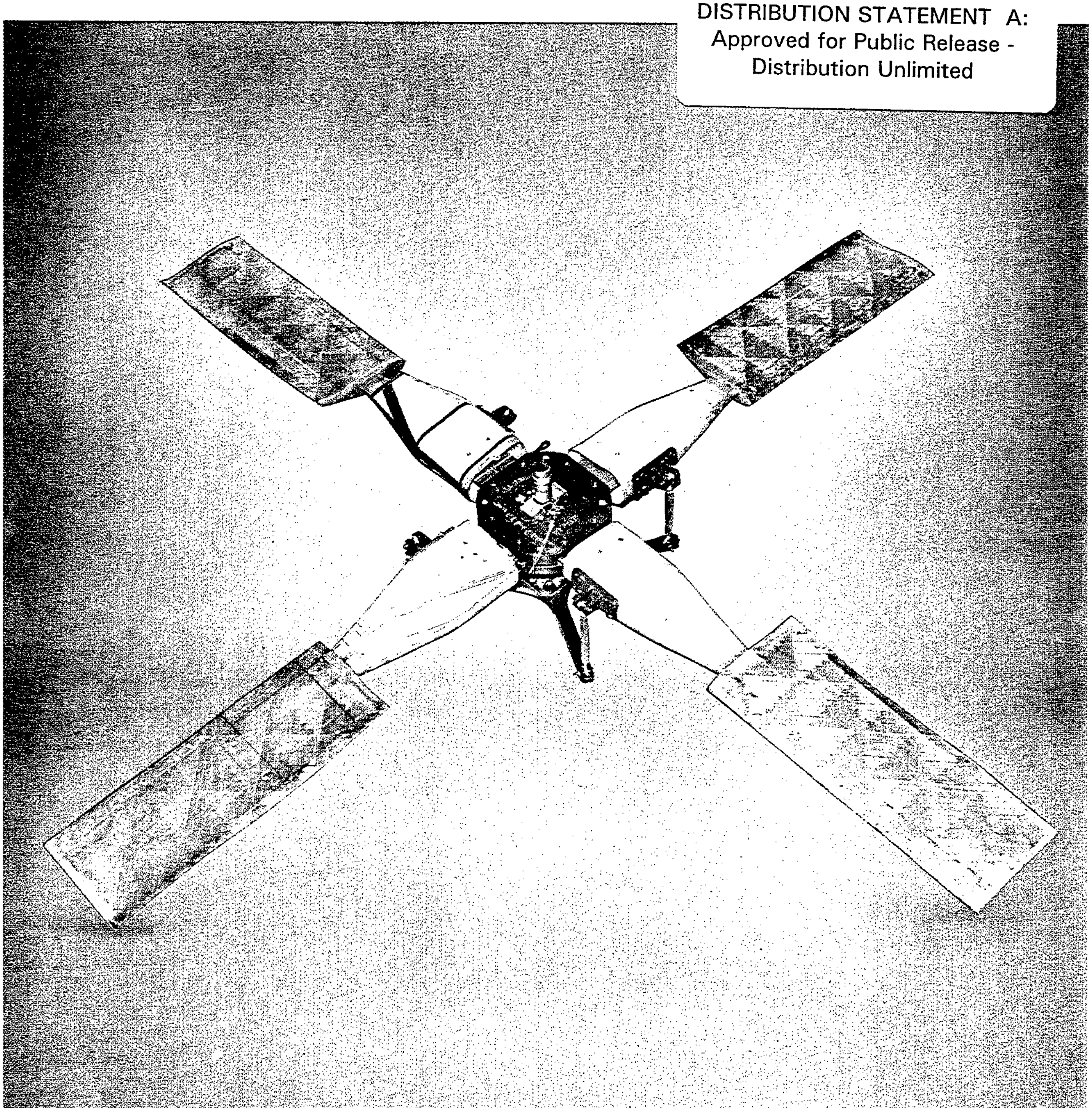
US Army

ManTech Journal

Pioneering Composite Fabrication

Volume 9/Number 2/1984



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Contents

About the Cover

Improved performance, fatigue life, and damage tolerance combine with reduced acquisition and operating costs in this composite flexbeam tail rotor (see article on page 3). Production design and manufacturing technology developed during a U.S. Army Aviation Systems Command mantech program features a low-cost wet filament winding fabrication technique and optimum composite materials. The development constitutes a low risk improvement to the Apache weapons system; two blade pairs are mounted at 90 degrees to the hub with elastomeric shear pads that significantly reduce hub loads and provide unique dynamic characteristics.

THE MANTECH JOURNAL is prepared quarterly for the U.S. Army under the sponsorship of the Directorate for Manufacturing Technology, DARCOM, by the Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, through the Metals and Ceramics Information Center, Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201.

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Comments by the Editor


RAYMOND L. FARROW

One of the most significant milestones in the nearly 20 years of manufacturing technology programs of the Department of Defense has been announced since our last publication of the U.S. Army ManTech Journal. This milestone is reflected by the formal establishment of the Manufacturing Technology Information Analysis Center, a DOD agency that will be monitored by personnel from the U.S. Army Materials & Mechanics Research Center, Watertown, Massachusetts. Mr. David Seitz, who also serves as Associate Editor of the Army ManTech Journal and directly oversees most of its operation, will serve as Contracting Office Technical Representative.

Establishment of the MTIAC represents the culmination of many years of planning and discussion among officials of the Department of Defense and was a much sought after program, with over half a dozen highly reputable organizations entering bids for the project. The basic agreement entered into with Case & Co., Inc., the Chicago based winner of the competition—with support of the IIT Research Institute, calls for a minimum appropriation of $500,000 per year for the first three years with an option for two more years. Related projects could increase the size of the project to well over $1 million each year.

The objective of MTIAC's operation is to support the DOD Manufacturing Technology Program in achieving its goal of improving the productivity and responsiveness of the defense industrial base. The MTIAC will also support other government agencies and their contractors. The MTIAC will provide technical and administrative support to the DOD Manufacturing Technology Advisory Group (MTAG) and also support the private sector.

The MTIAC will serve as an authoritative information source on manufacturing technology. It will establish and maintain data bases and will be responsible for collecting, reviewing, analyzing, appraising, and summarizing available manufacturing technology data and information. The Center will provide varying products and services involving the following areas:

Handbooks and Data Books—engineering reference works containing authoritative scientific and engineering data and information.

State-of-the-Art Summaries—special studies on high interest technology.

Critical Reviews and Technology Assessments—generally exceeding the scope of a technical inquiry response but considerably smaller than a state-of-the-art summary.

Technical Inquiries—scientific and engineering analysis of available information made available via letter or telephone.

Abstracts and Index—abstracts of reports related to manufacturing technology, bound and indexed.

Bibliographic Inquiries—extracted information and references in list format.

Special Studies/Tasks—additional services such as detailed solutions to narrow scope problems, technical consultation, and logistics coordination of MTAG activities.

Acquisition and Input of Source Information—collection, review, analysis, cataloging, and storing of information on MTP investments and other pertinent literature.

User Accessible Data Base—an on-line information system accessible via telephone.

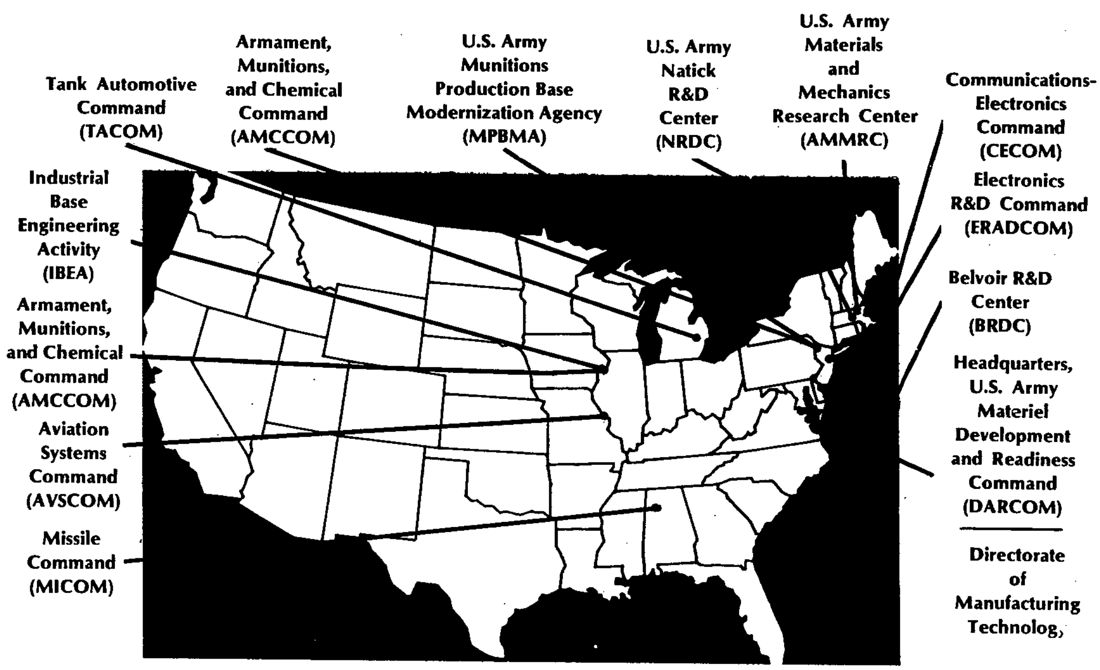
Current Awareness Program—recurring newsletters highlighting current affairs in manufacturing.

The Center comes at a time when the body of information generated through the years by the mantech program is increasing in archival importance and new data is being acquired at a record pace. This publication has served since its inception 8 years ago both the Department of Defense and industry as the most comprehensive focused source for U.S. Army manufacturing accomplishments, but the Center will provide a new, broader perspective of manufacturing technology, both in the defense and industrial sectors.

The manufacturing technology program recently has drawn most favorable comments from industry media and currently enjoys the confidence of high officials in government. The Center should further enhance this perception.

The MTIAC is scheduled to begin operations late in 1984. Additional information is available from David Seitz, U.S. Army Materials and Mechanics Research Center, AUTOVON 955-5527, Commercial (617) 923-5527; or the MTIAC Director, Thomas Turner, Case and Company, (312) 567-4730 or (312) 861-0994.

DARCOM Manufacturing Methods and Technology Community



Performance, Fatigue Life, Damage Tolerance Better

Composite Flexbeam Tail Rotor Practical

SEYMOUR H. WIESENBERG is an Industrial Engineer at the U.S. Army Aviation Systems Command with the Project Manager's Office for Tactical Airborne Remotely Piloted Vehicles. He was the PE on the program that developed the composite flexbeam tail rotor while assigned to the AVRADCOM Manufacturing Technology Program. During his 15 years of industrial experience, he was heavily engaged in quality engineering at General Electric before joining the Government engineering staff. He received his B. E. in Industrial Engineering from New York University and his M.B.A. from the State University of New York at Buffalo.

Fabrication of a successful flexbeam tail rotor by the U.S. Army Aviation System Command has been possible through use of a wide range of state-of-the-art composite manufacturing techniques, with emphasis upon automated wet filament winding. Techniques included manual layup and wet filament winding; vacuum bag, internally pressurized split mold, and autoclave curing; and disposable foam mandrel, plaster, steel, and high temperature epoxy tooling.

The objective of this project conducted by Hughes Helicopters, Inc., was to refine and verify the manufacturing processes and production configuration for a composite flexbeam tail rotor for the AH-64 Apache Attack Helicopter. The program was structured to consist of design refinement, manufacturing methods development, tooling development, fabrication of test components, structural laboratory tests, and wind tunnel testing.

When fully implemented, the composite flexbeam tail rotor will provide several important benefits including:

- Improved tail rotor performance
- Reduced acquisition cost
- Reduced operating cost
- Improved fatigue life
- Reduced parts count
- Improved damage tolerance/survivability.

The composite flexbeam tail rotor development effort follows the modern trend to incorporate advanced composite structures in ever increasing applications in Army aircraft to realize the advantages of decreased weight and life cycle cost. The wet filament winding cocure process has been demonstrated as a viable approach for reducing labor requirements in the construction of composite

NOTE: This manufacturing technology project that was conducted by Hughes Helicopters was funded by the U.S. Army Aviation Systems Command under the overall direction of the U.S. Army Directorate ror Manutacturing Technology, DARCOM. The MICOM Point of Contact for more information is Bill Brand, (314) 263-3079.

components while utilizing raw materials at their lowest cost and providing a repeatable/reliable structure.

Hughes Helicopters designed and built a full-scale prototype bearingless tail rotor under an independent research and development program and verified the concept in a 10-hour whirl test in mid-1979. This MM&T program further refined the design and manufacturing technology to be fully compatible with the production Apache helicopter.

Kevlar Used in Blades

The composite flexbeam tail rotor was designed in accordance with all structural and environmental requirements for the metal tail rotor blade. Compatibility with the GE-T700 increased performance engine also was required. A ±5 degree glass fiber/epoxy flexbeam connects the wet filament winding Kevlar/epoxy blades to the hub, within which elastomeric shear pads allow the flexbeam to bend freely. A pitch case transfers pitch control loads into the blade, and shear supports center the pitch case about the flexbeam. The Kevlar blade is of wet filament wound tubular construction. This design was shown analytically to have good dynamic characteristics and to be free from aeroelastic instability.

An exploded view of the composite flexbeam tail rotor (Figure 1) shows that the spanwise axes of the blade-pair assembly are perpendicular to each other and are separated axially so one flexbeam may cross over the other. The rotor has upper and lower hub plates which sandwich the blade-pair assembly. The hub assembly is bolted to the tail rotor drive shaft. The flexbeam extends from one blade across the hub to the opposite blade. Bending and twising motion of the flexbeam between the edge of the hub and the inboard end of the blade provides the fundamental flap, lag, and torsional motions of the rotor blades. The flexbeams are attached to the hub plates through elastomeric shear (in-plane) pads. These pads are bonded to the flexbeam on one side and are mated to the hub through the clamping bolts. The pitch case transmits pitch link (feathering) motion to the blade. The laminated elastomeric pitch shear support aligns the pitch case with respect to the flexbeam. The pitch horn

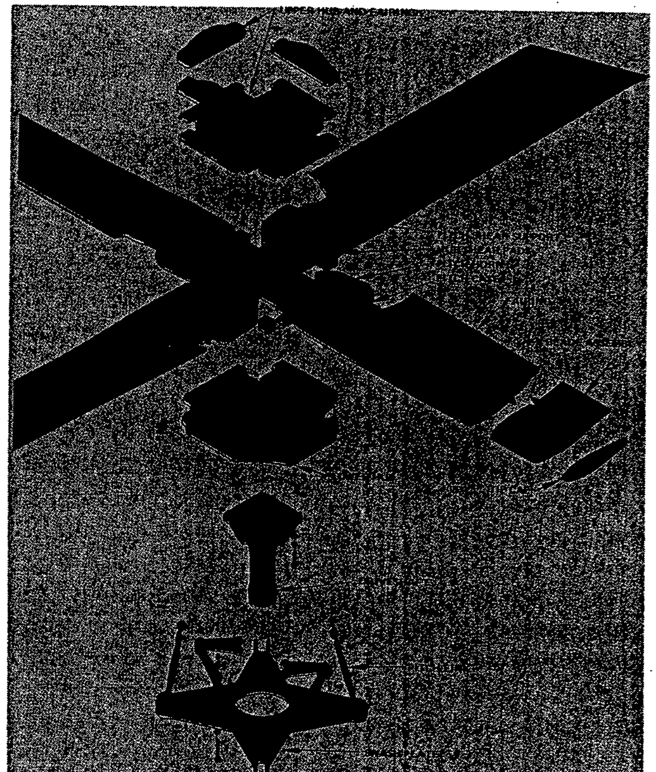


Figure 1

is bolted to the trailing edge of the pitch case. The spanwise location of the pitch link attachment is designed for an effective pitch-flap coupling of −35 degrees (pitch down with flap up). The pitch link is inclined to provide negative pitch-lag coupling (pitch up with blade lag). The rotor diameter is 112 inches and its blade chord is 11 inches, which includes a trailing edge tab of 1.1 inches. The blades have an NACA HH-02 airfoil at the tip, transitioning to a modified 17 percent thickness HH-02 airfoil at the root.

Design Ground Rules

The criteria and requirements that directly influenced the composite flexbeam tail rotor design are as follows:

(1) Adopt rotor blade external geometric properties for optimum performance for the GE-T700 engines.

(2) Design for compatible dynamic operation on the AH-64.

(3) Design, as a minimum, to existing metal tail rotor blade reliability and maintainability requirements. Place strong emphasis on a high level of field repairability.

(4) Select and use nonmetallic structural filaments stabilized in an epoxy matrix to the maximum practical extent.

(5) Design for a fatigue life of 4500 operating hours.

(6) Design every part to be invulnerable to a tumbled 12.7 API projectile strike. The rotor shall be capable of continued safe operating 30 minutes after the strike.

Significant differences in geometry between the metal tail rotor and the composite flexbeam tail rotor existed. First, azimuth blade spacing is 55 degrees for the metal tail rotor and 90 degrees for the composite flexbeam tail (as shown in Figure 2). The 55-degree configuration was originally chosen to minimize disassembly for air transportability. But the stretched version of the C-141 transport no longer requires a folding tail boom and 55 degree tail rotor. Second, the axial spacing between composite flexbeam tail rotor blade pairs is 0.65 inch, compared to the 4.90 inch spacing of the double teetering metal tail rotor. The 55-degree spacing of the metal blades required enough axial separation to avoid blade/pitch horn interference. The 90-degree spacing allows closely stacked flexbeams and a more compact hub design. Third, the pitch horn attachment was changed from the leading edge as in the case of the metal rotor to the trailing edge for this rotor. This change assured positive stability over the collective pitch range and eliminated a 3/rev resonance in the second chordwise bending mode. However, when diameter and chord of the rotor were increased to 112 inches and 11 inches, respectively, from the Phase II metal tail rotor diameter of 110 inches and chord of 10 inches. This change was made to provide increased tail rotor thrust for controllability of the AH-64 with the more powerful T700 engines.

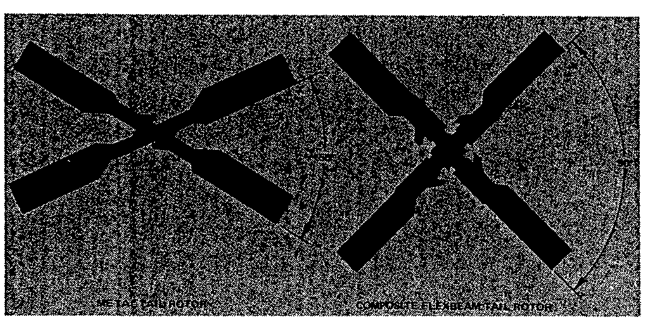


Figure 2

Higher control loads result from a larger rotor; this would have been incompatible with the tail rotor control system. So the existing airfoil was changed to an HH-02 section at the tip, varying linearly to a similar 17 percent thick airfoil at the root. At the same time, the tab angle was changed from +6 degrees (trailing edge down) to 0 degrees. The combined result was acceptable control loads and an improved controllability ceiling.

Lightning, Ballistic, and Erosion Protection

A qualitative rotor vulnerability study was performed comparing the current design of the rotor with the baseline AH-64A metal design. The vulnerable area due to impacts by 12.7-mm API projectiles may be totally eliminated upon validation of the flexbeam detail design. If so, an invulnerable tail rotor would decrease the vulnerable area of each ship due to the 12.7-mm API threat by 16 percent compared to the baseline design. The vulnerability attributed to the 23-mm HEI threat can be expected to decrease by a minimum of 10 percent, due primarily to the less critical blade balance weight location on the pitch case rather than at the tip on the metal tail rotor.

The major portion of the vulnerable area reduction would be accomplished by demonstration that the flexbeam within the hub area is tolerant to the worst case

penetration damage of an armor piercing projectile. Due to the hub design of the composite tail rotor, parts or all of the swashplate assembly are not ballistically critical. The blades are also invulnerable due to the effect of its large size. The pitch links are lightweight members designed only for flight loads—API strike loads are not considered. It has been demonstrated with flexbeam rotors that when a pitch link breaks, its blade twists back to near zero lift condition and remains stable. Hence, armored pitch links are not necessary.

The criteria applied in the design for lightning protection of the composite flexbeam tail rotor included the following ground rules:

- Repairable damage from strikes up to 50,000 amperes
- Ability to return to base after 200,000 amperes strike
- No significant cost penalty
- No significant weight penalty.

Lightning tests conducted as part of a company funded program on subscale components representing rotor blades and fuselage structure—fabricated from Kevlar, glass, and graphite epoxy materials—have established an understanding of the effect of lightning on composite structure. In the case of a structure fabricated from nonconductive material such as glass or Kevlar, strikes will circumvent the structure even when placing the electrode almost in direct contact with the structure surface. However, the conductive material buried within the structure (such as balance weights) attracts lightning, and if not properly grounded will cause significant damage.

With the exception of the leading edge steel rod balance weights and the steel erosion strip, the rotor is completely nonconductive. Therefore, it was recommended that no additional protective material such as metallized wire mesh screen be required for lightning protection. All metallic material substructure such as the balance weights and backing strip will be properly grounded to the hub.

Polyurethane was selected to protect the rotor leading edge from sand and rain erosion for the following reasons. First, although its resistance to rain is poor relative to nickel (another good antierosion material), an inordinate amount of rain for an unusually long period of time is required for erosion to occur. Next, the cost per blade is small and it can be repaired or replaced easily. Last, it is used successfully on the CH-53 main and tail rotors and Westland WG-13 main rotor blades.

In the event of premature loss of the polyurethane strip, a preformed 0.015-inch stainless steel strip was added below it in the high erosion rate, outboard area only of the leading edge.

Structural Analysis

The structural integrity of the rotor was established analytically and verified later by a series of laboratory static and fatigue tests. Specifically, analytical static and fatigue substantiation of the AH-64 system included design criteria, material allowables, calculated minimum margins of safety, and summary analyses of structurally critical areas. Based on this analysis, there will be no failure at ultimate load (1.5 x limit load), negligible permanent set under limit load, and the fatigue life will be equal to or greater than 4500 hours, the design life of the AH-64. In addition, with a failed critical structural element (e.g., one bolt in a 4 bolt joint), the composite flexbeam tail rotor will be capable of taking limit loads as ultimate, without further failure.

Design loads were calculated from the AH-64 flight spectrum. An unbalanced blade strike load of 2395 pounds is derived from the condition whereby the outer 10 percent of one blade is sheared off. This load was minimized by terminating the steel leading edge rods at a point which is 90 percent of the blade radius. Vulnerability, ground, and weapons blast loads are relatively small and did not influence the design.

The static, mechanical, and physical properties of ±5 degree S-2 glass/epoxy and unidirectional Kevlar/epoxy, the two primary composite materials in the rotor, were obtained. Tension and shear fatigue allowables were obtained from Hughes test data, published data, and the con-

struction of Goodman diagrams. Figure 3 is a graph of the axial, flapwise, chordwise, and torsional stiffnesses of the flexbeam. Pitch case, blade axial, flapwise, chordwise, and torsional stiffnesses were also calculated.

A listing of analyzed components and associated minimum margins of safety were compiled. The margin of safety for both metallic and composite parts is based on ultimate loads, which are 1.5 times limit load. The most critical area is the flexbeam/pitch case joint, with a static margin of safety of 0.09 and fatigue margin of 0.02.

Manufacturing Development—A Building Process

Fabrication of the composite flexbeam tail rotor involved a wide range of state-of-the-art composite manufacturing techniques, including manual layup and automated wet filament winding of the composite materials; vacuum bag, internally pressurized split mold, and autoclave curing; and disposable foam mandrel, plaster, steel, and high temperature epoxy tooling. Composite blade manufacturing experience at Hughes Helicopters was based initially on the Multi-Tubular Spar (MTS) program and the Composite Main Rotor Blade (CMRB) program for the AH-64. Integration of this experience into the rotor design began when Hughes fabricated a full-scale prototype rotor using simplified plaster tooling and, for the most part, manual layup of composite materials. Then, during the MM&T program, improved tooling was fabricated, wet filament winding and other processing refinements were instituted, and detailed records of labor and material costs were maintained for future learning curve and cost reduction analyses. An overall flow diagram of the assembly sequence is presented in Figure 4.

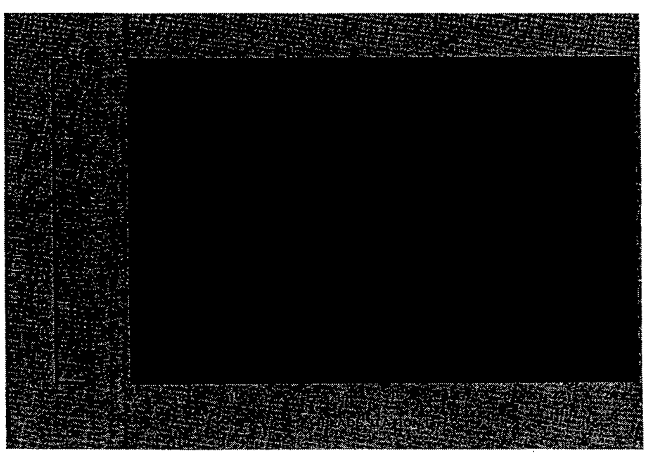


Figure 3

Quality Assurance acceptance criteria were prepared to verify that each component was produced according to engineering drawings, specifications, and production documents. Major areas for which test plans were implemented included:

- Receiving inspection for materials
- Resin preparation and wet filament winding
- In-process assembly and final inspection
- Nondestructive (light-through transmission, ultrasonics, and X-ray) inspection.

All test results were recorded and have been maintained so that maximum future benefit may be realized from this development program. Lot or batch number of materials used in each tail rotor were recorded. Equipment and gages used to control or measure materials and processes were periodically calibrated according to Hughes Helicopters' calibration procedures and were approved by Army personnel.

Coupon/Element Test

The two critical areas tested with full-scale components were the flexbeam root-end and flexbeam/pitch case attachment area. In addition, numerous coupon tests were conducted to determine the physical, static, and fatigue properties of materials used and the strength of primary bonded joints.

The selected flexbeam material, NARMCO 5216 S-2 glass prepreg, was qualified to the appropriate Hughes Helicopter material specification. In addition to these standard tests, which included tensile tests of coupons with 0 degree fiber orientation, tensile and interlaminar

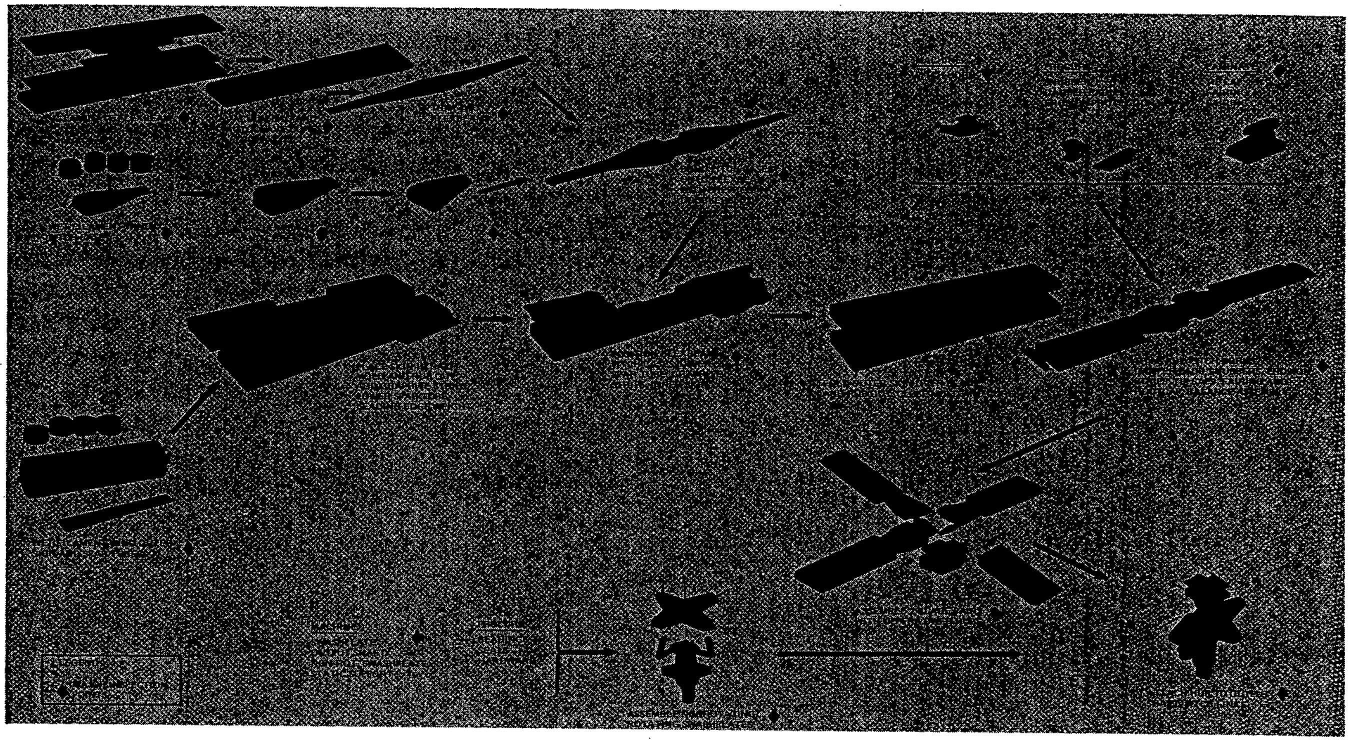


Figure 4

shear tests were conducted on ±5 degree fiber orientation coupons. The ±5 degree tensile test specimen is shown in Figure 5. The width was varied to observe its effect on tensile strength, since a relatively narrow specimen will have fewer continuous fibers extending between the two tabs than a wider one. Results of these tests were plotted. The short beam shear specimen was in accordance with ASTM 2344 except for width, which was increased to 0.5 inch to increase the percentage of full length ±5 degree fibers. The results are indicative of a high quality laminate.

The tension fatigue strength allowable of the ±5 degree S-2 glass/epoxy flexbeam material was determined experimentally by testing seven coupons. One set of four coupons was fabricated with Composites Horizons CH3060 resin system and a second set of three coupons used the APCO 2434/2347 resin system.

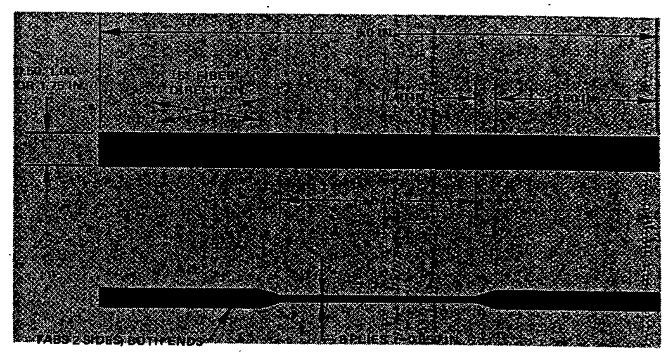


Figure 5

Physical property determination of the flexbeam was an important parameter, both in the early stages of material selection and development and during the fabrication of each flexbeam. The material selected was NARMCO 5216 S-2 glass unidirectional prepreg, rather than S-2 glass wet

filament winding in-house with APCO 2434/2347 resin system because of better handling qualities and more consistent resin content. Laminate fiber volume was initially targeted at 60 + 3 percent in order to maximize tensile strength.

Two sets of test panels, one set with 6 or 7 plies simulating the thinnest outboard region of the flexbeam and the other set with 66 to 80 plies that simulate the thickest root-end area of the flexbeam, were autoclave cured with varying numbers of bleeder cloths. The fiber volume of the thin panels was about 62 percent, but the thick panels maintained a fiber volume of about 55 percent. The reason for the lower fiber volume was the incomplete resin bleedout from the interior of the thick laminate prior to resin setup. Since the strength of the laminate was still adequate, two-third scale (in length only) flexbeams were fabricated. Thinner areas of the subscale flexbeams had acceptable fiber volumes, while the full thickness (0.57 inch, 68 ply) areas had an average fiber volume of 54.88 percent. During the course of full-scale flexbeam fabrication, physical property specimens were taken from the midsection of the laminant between each flexbeam.

Joint Shear Strength Checked

A second series of coupon tests investigated the shear strength of the joints between (1) the flexbeam and pitch case doubler and (2) the flexbeam and spar tube. The substrates were designed and fabricated to simulate the respective full-scale structures as closely as possible. The double lap was varied to give a 0.5, 1.0, and 1.5-inch length to determine its influence on structural efficiency (average shear strength).

The adhesive for the pitch case doubler/flexbeam joint was Hysol EA 9528, while the spar tube substrate was cocured without adhesive to a precured flexbeam substrate. Similar pitch case doubler/flexbeam specimens made with ±5 degree S-2 glass fiber and APCO 2434/2347 resin system were also tested for initial evaluation and comparison. Except for one data point, the adhesively bonded prepreg substrates appeared stronger than the cocure system. This fact, combined with its handling ease during layup, provided the basis for selection of the prepreg for the pitch case/flexbeam doubler. The average shear strength of four flexbeam/spar tube, 0.5 inch long shear specimens was 2269 psi.

Wind Tunnel Tests Performed

Wind tunnel tests were successfully performed to verify the performance, loads, and dynamic characteristics of the design for rotor speeds up to 100 percent of design operating rotor speed and airspeeds up to 197 knots. A complete pitch range was investigated in hover, low and high speed forward flight, and sideslip conditions.

An assessment of composite flexbeam tail rotor characteristics from the voluminous amount of data gathered during the wind tunnel test was categorized as follows: performance, structural fatigue, dynamics, and blade loads. Correlation of test data is made with analytical predictions and load limits of structural components wherever possible. But because the design was tested as an isolated rotor system without the blockage effects of the AH-64 vertical tail, the various test conditions cannot be directly correlated with predicted flight cases.

A comparison of the measured collective pitch angle at 75 percent radius with thrust coefficient versus the theoretically predicted collective pitch angle shows higher pitch angles required to produce the same thrust when compared to the predicted pitch angles. This has been the case in previous comparisons with measured full scale main and tail rotor data. Part of this pitch difference may be in the zero lift pitch angles of the test rotors. Further investigation will be required to resolve the difference in pitch angles.

Structural Fatigue Determined

The structural evaluation was limited to the comparison of measured loads with the endurance limit and the 1-hour limit established for each structural member. These are the same alternating load or stress limits used as criteria to monitor the rotor structural response during the wind tunnel test.

One or both of the monitoring limits were exceeded

in a few test conditions. These occurrences are primarily useful to indicate areas for additional investigation which are beyond the scope of the present work. For example, it needs to be determined whether each test point which produced excessive alternating load lies within the actual flight envelope. If so, its frequency of occurrence within the total spectrum of flight loads would need to be determined in order to assess its effect on the service life of the affected structural member.

Flexbeam test stresses due to flapwise and chordwise bending were well below the endurance limit except at one point where 8.5 degrees right sideslip at 197 knots produced an alternating corner stress 30 percent greater than its endurance limit but 14 percent less than the 1-hour limit. However, it should be noted that the corner stress is based on the conservative assumption that flapwise and chordwise moments peak simultaneously.

Pitchlink test axial load exceeded its endurance limit at speeds above 161 knots and its 1-hour limit above 190 knots. These pitchlink load limits were actually used to monitor the pitchhorn. A minor modification of the pitchhorn would raise both limits well above the test loads measured. Rotor mast test bending moment reached 99 percent endurance limit at 197 knots. If needed to satisfy actual flight envelope requirements, minor dimensional modifications would increase this margin. The output driveshaft test bending moment did not exceed 51 percent endurance limit. Upper and lower hub test stresses did not exceed about 6 percent endurance limit.

Future Work

The MM&T program successfully developed a production design and manufacturing technology for the Apache helicopter flexbeam tail rotor. Fabrication techniques incorporated low-cost wet filament winding and an optimum amount of composite materials. The design and analysis were confirmed through laboratory and wind tunnel testing. The conclusion is that the composite flexbeam tail rotor can be a low-risk improvement to the Apache weapons system.

It is recommended that future work be initiated in accordance with the Airworthiness Qualification Specification, which includes an analytical evaluation of the composite flexbeam tail rotor on the Apache; laboratory, flight, and environmental tests; and modifications to the Apache helicopter required for composite flexbeam tail rotor implementation.

Significant Payback in Life Cycle Costs

Low Cost, Reliable Electromagnetic Components

BOBBY L. AUSTIN is a Project Engineer and Technology Transfer Manager of the Manufacturing Methods and Technology (MMT) Program at the U.S. Army Missile Command, Redstone Arsenal, Alabama. He is a graduate of the University of Alabama with a B.S. Degree in Aeronautical Engineering and is a graduate of the U.S. Army DARCOM Intern Training Center, Product/Production Engineering Program. He also holds an M.S. Degree in Systems Management from the Florida Institute of Technology. Bob currently is assigned to the Manufacturing Technology Division of the System Engineering and Production Directorate. He has been affiliated with the MMT Program since 1978. He has served as an MMT Project Manager; developed and manages the MMT management information system; has served on manufacturing process plan and production readiness review teams for various Army missile systems; and is a member of the Tri-Service Manufacturing Technology Advisory Group (MTAG) CAD/CAM Committee.

Electromagnetic component manufacture took a quantum leap technologically as a result of a U.S. Army Missile Command MMT project that has been done by Hughes Aircraft. A multitude of new techniques for the manufacture of low cost, high reliability core type transformers/inductors for missile system applications were examined and evaluated. Molding technologies, winding techniques, curing procedures, and encapsulation processes were topics considered in extreme detail. Over 40 encapsulation thermosetting compounds for high reliability components were investigated, with two selected for their low stress and high voltage, corona free applications, respectively.

The Phase I effort concentrated on improving the manufacturing methods of potting, encapsulation, and winding of electromagnetic devices, while the follow-on phase (Phase II) investigated interconnection techniques, tooling, and structural parts. Implementation of the combined results of both of these efforts should improve manufacturing methods for electromagnetic components so that a significant payback will be obtained in manufacture and life cycle costs of missile systems due to lower production costs, higher process yields, and improved reliability.

Methods of Potting/Encapsulation

An in-depth investigation of over 40 encapsulation compounds was made to identify those which would have the optimum parameters for encapsulation or potting of electromagnetic components for missile applications. Proposed values of 36 parameters were established, against which each compound was evaluated. In many cases data

NOTE: This manufacturing technology project that was conducted by Hughes Aerospace was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Directorate for Manufacturing Technology, DARCOM. The MICOM Point of Contact for more information is Bobby Austin, (205) 876-2147.

was not available from the vendor, so tests were made to obtain the required information to facilitate comparison. One of the most critical parameters is the glass transition temperature of the resin, below which many materials exhibit a rapidly rising compressive stress. Such stresses applied to strain sensitive cores during temperature cycling can adversely affect the functional response of magnetic components. A direct measurement of these stresses, ranging as high as 6000 psi at −40 C, was made using pressure calibrated mercurial thermometers. A two-step process, using soft material first to cushion the core from the stresses generated by the final material, was investigated. This method showed some reduction, but was not comparable to the low stress materials evaluated.

As would be expected, no one resin was a universally ideal encapsulation material. Trade-offs of parameters and properties are required for each application. The five materials which were judged to have the most acceptable combination of parameters, including compressive stresses of less than 200 psi at the lowest temperatures, were Epon 825 with HV hardener; Scotchcast 255; Eccoseal 1218; Hysol C-60; and Hysol C15-015. As an example of the trade-offs only, the Epon 825/HV was corona-free during high voltage tests; the other four had varying degrees of corona present. On the other hand, for low voltage applications under 250 V peak, some of the others had more optimum parameters. This information would assist the designer in making the proper selection of encapsulating material for a high reliability magnetics application and also help the manufacturer in setting up the proper processing and handling procedures to produce a cost effective, reliable part.

Special Considerations

It is recommended that a standard set of test conditions to obtain the required data for new resins should be established to allow comparison with existing materials for high reliability applications, especially for determination of electrical properties. Mechanical and thermal properties are covered fairly well by ASTM procedures. Further, a major source of failure in encapsulated magnetic components wound with fine wire is breakage of the leads between the coil and the terminals caused by thermal expansion of the resin. Intermediate leads of AWG 36 or larger should always be used. The test assembly used in this work is shown in Figure 1.

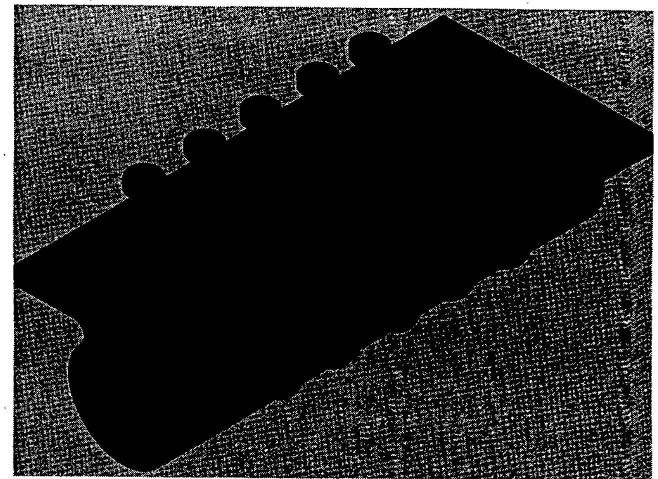


Figure 1

Pressure sensitive magnetic cores and other fragile electronic components require low stress potting/encapsulation techniques and materials. Quantitative measurements of stress as a function of temperature are needed to properly evaluate a material.

A method of hydrostatically stressing small magnetic components to 10,000 psi was also developed. Ferrites, moly permalloy powder (MPP), and tape would cores were exposed to this pressure level, with very small effects. Later tests showed that unbalanced rather than isotropic stresses significantly altered the magnetic properties.

Conap EN-9, Conap EN-9-OZR, Uralane 5753, RTV 615, RTV 619, RTV 627, and RTV 655 showed less than 200 psi at −40 F, with no apparent glass transition temperature reached. The use of a high stress material over a low stress encapsulant to reduce the overall stress generated was partially successful, but was far from the 200 psi arbitrary limit selected as acceptable.

Finally, for high voltage applications, Epon 825/HV was the only material that showed zero corona level. Scotchcast 255 and Eccoseal 1218 had high corona levels at the same applied voltage, although their dielectric strength was sufficient to prevent short-term breakdown.

Controlled Winding Techniques

The controlled winding techniques task addressed four areas: wire handling, contamination, solenoid and transformer coil (bobbin) winding, and toroidal coil winding. The obvious observation that, in order to produce a reliable component, the materials being used must be of

highest quality, is doubly true for the wire used in winding electromagnetic components. The wire handling and contamination investigation concluded that spools of wire, especially the fine and ultrafine gauges, should be encased at all times in foam plastic protective enclosures and inserted into plastic bags, except when wire is being removed at the winding station. The smaller sizes of wire are especially susceptible to damage from dropping, which damages the spool, and objects striking the wire, interfering with the unwinding process. Exposure of the unprotected spool to contaminants of any kind—either airborne or liquid splashes—or handling without gloves will degrade the encapsulation process. Yet it was interesting to note that no such precautions were taken in any facility that was visited. In most cases the spools of wire were stacked in open stockroom areas without any protection whatever.

An analyisis of the tension factors involved in winding many layers of ultrafine wire on square bobbins, followed by fabrication of actual coils using normally accepted tension figures, revealed a cumulative wire and insulation deformation effect which apparently has not been reported in the literature. Using accepted tension levels of the industry which are calculated to stress the ultrafine wire well under its elastic limit, a buildup of internal radial pressure (IRP) at the corners of the bobbin was sufficient to compress the insulation tightly together, eliminating all voids; also, plastic deformation and flow of the copper occurred. Slippage or cleavage planes of groups of conductors through the winding was also seen in sectioned coils. The analysis showed that the factors involved were the winding tension, wire diameter, numbers of layers, and initial radius of curvature of the corners of the bobbin. Tensions less than 42 percent of rated were required to prevent this damage. Rounding the corners of the bobbin sufficiently will reduce the IRP and achieve a damage-free winding. No problem exists if a round bobbin is used at standard winding tensions.

Anomalies Encountered

A hidden source of wire damage was also uncovered in the toroidal winding investigation. Realizing that a certain amount of skill is required of winding personnel in positioning the toroid so that the shuttle does not scrape the insulation from the windings already on the toroid, a method of detecting this possible damage was proposed. An alarm circuit (Figures 2 and 3) was developed

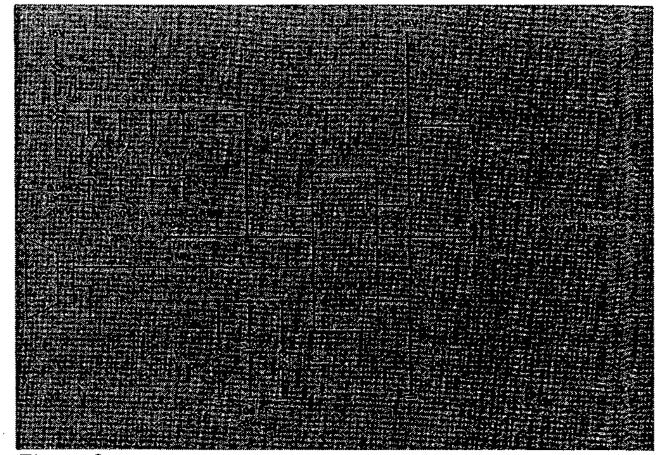


Figure 2

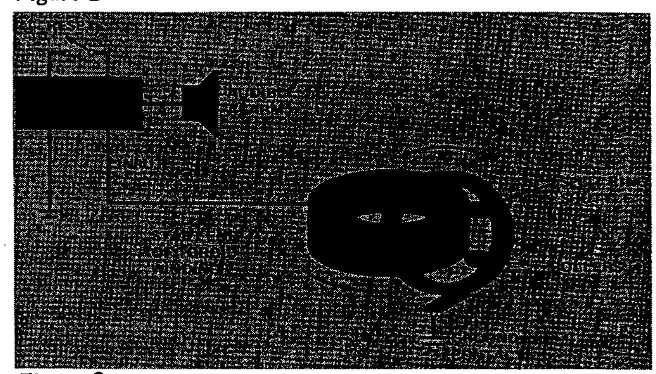


Figure 3

which would detect a momentary electrical contact between the shuttle and the wire it carried. For higher reliability components it is proposed that tripping of the alarm during winding would be cause for rejection, thus saving the cost of further manufacturing a defective part.

An additional benefit of the device was found to be a continuous monitoring of wire insulation integrity, not before possible. Conventional QA acceptance of fine wire is to take a few feet off the end of the spool and perform the requisite tests, assuming that this is representative of wire quality throughout the spool, which may or may not be true. During the development of the circuit, while winding toroids, the alarm was tripped several times with no obvious contact of the shuttle and the windings. Since the wire being used was from an old spool, it was scrapped and a new spool substituted; the problem went away. When the cause was finally pinpointed as probably due to defective wire, the old spool had been discarded and was not available for confirmation.

When toroidal windings were being made for the MM&T program, another anomally was encountered, in that the alarm would trip randomly. Since this time the wire insulation quality was nominal, the cause was traced to the shuttle ring itself. The split in the shuttle ring which accommodates the toroidal core was found to scuff the insulation of the fine wire during the loading and subsequent winding operation to the extent that not only was the insulation penetrated, but sometimes a notch was made in the copper itself. A small piece of tape placed across the split prior to loading of wire corrected the problem, which apparently is not done in usual practice or required in general winding specifications.

From the above it is concluded that such a monitoring device used on all toroidal winders would improve the reliability and reduce costs by early detection of damage and localization of problems for all sizes of wire.

In conjunction with the bobbin and toroidal winding investigations, a study of the various methods of wire tension control was made. Such devices have been in use for many years, with no new approaches found applicable to fine wire. Also included is a suggested check list for setting up a toroidal winder for fine wire winding.

Interconnection Techniques

Five different areas were covered during the project, namely, stripping of wire insulation; techniques for joining ultrafine coil wires to intermediate lead wires; size requirements for intermediate leads; techniques for terminating ultrafine wire; radii of connections as a function of operating voltage, including methods of making low cost, reliable connections in high voltage components.

A survey of the various methods to remove magnet wire insulation, which included heat, abrasive, laser, and chemical, was made and compared. No clearcut method of insulation removal was found that did not have significant disadvantages.

A method investigated which appeared very promising at first was the removal of the insulation by a stream of abrasive particles propelled by a small air blast (Figure 4), which removed insulation readily including the high temperature ML materials. Initial tests run on large wire sizes showed an effective removal of insulation without eroding the copper conductor itself. Nozzles were designed to impinge fine wire on all sides so that it would not have to be rotated to completely remove the insulation;

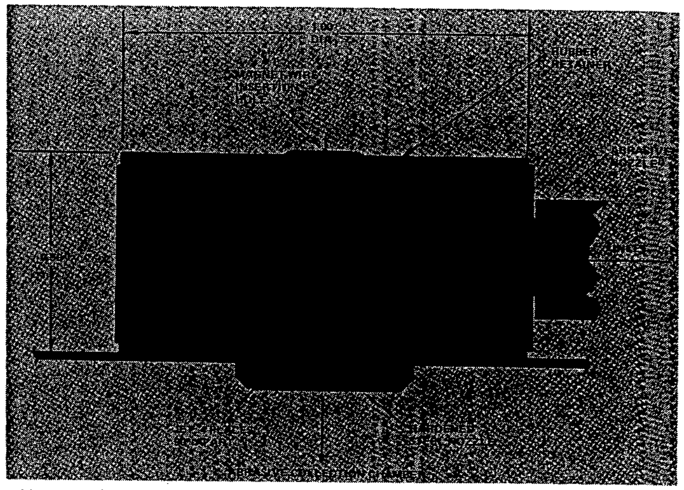


Figure 4

however, adverse effects on solderability and mechanical properties caused further work to be discontinued. Insulation removal with the carbon dioxide laser showed promise with the larger wire sizes, but further work is required for application to fine wire gauges in a production environment.

Various techniques for connecting fine and ultrafine magnet wires to intermediate lead wires were investigated. As a general rule, wire sizes smaller than AWG 36 should not be routed through encapsulation materials for any great distances, because the thermal expansion of the material can cause breakage. The normal procedure is that, after winding a fine wire or ultrafine wire coil, the insulation is removed and an intermediate lead wire soldered in or otherwise connected and the resulting joint taped down on the winding. The intermediate wire then goes to the terminals to connect to the outside world.

Since tin-lead solders are capable of dissolving fine copper wire during the soldering operation, other solder formulations were investigated. Also, other methods of achieving a low resistance joint (Table 1) were investigated, such as welding, laser welding, crimping, and the use of conductive adhesive materials. The conclusion was that careful control of all soldering parameters, including soldering temperature, time, and size of the iron, would allow joints to be made with fine wire without significant dissolution using conventional tin-lead solders.

During encapsulation of high voltage transformer windings, extensive care is taken to prevent the occurrence of voids, which are a source of corona causing progressive

Attachment Process	Material	Number of Samples	Joint Resistance (ohms)		
			Min	Max	Avg
Solder Alloy	50% Indium, 50% Lead	10	0.022	0.053	0.040
	25% Indium, 75% Lead	7	0.015	0.064	0.041
	20% Tin, 80% Lead	9	0.030	0.065	0.046
	10% Tin, 88% Lead, 2% Silver	7	0.010	0.080	0.068
Conductive Adhesive	Eccobond 56C	9	0.056	0.099	0.080
Crimping	Lead Foil	[illegible]	0.089	0.50	0.21
Laser Welding	Magnet Wire	[illegible]	Not Tested		

Table 1

degradation of the insulation material. It is also considered imperative to eliminate any sharp points which may occur in the high voltage gradient regions. What has not been appreciated previously is that a sharp point in the high voltage winding can have a high enough voltage gradient to actually create voids in insulation where none originally existed. Once this void is created, the insulation begins to fail progressively, forming "trees." It was found that, when using diagonal cutters or scissors in cutting fine wire, the resultant sharpness of the cut increases the voltage gradient into the region where voids can be generated with only a moderate amount of high voltage applied to the winding. Caution must be especially taken in the termination of fine wire to the intermediate lead wire interface. A method of solder balling or putting a conductive sphere over the joint to control the gradient was investigated (Figure 5).

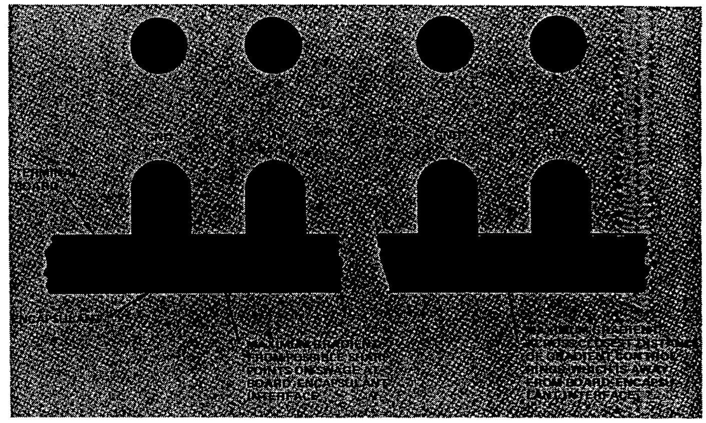


Figure 5

Tooling and Equipment for Encapsulation

This work addressed three areas: evaluate equipment and tooling to encapsulate devices with the processes developed in the basic program; determine the feasibility of automatic mixing and metering equipment; implement a continuous process for potting and encapsulation. A multiwinding, high voltage toroid with some windings using fine wire, and a high voltage biased, two-coil inductor with a C-core (Figure 6) were selected from missile programs as being typical components. Depending on the quantities involved, various molding systems were investigated, ranging from low production of a few hundred per month to high production of ten thousand or more per month. A major constraint in the design of the molds was that it was to minimize hand labor in the finishing and that the mold was to provide the outer surface of the component, as potting cups or covers were to be used. With the small and medium production runs, slush-type molds of low melting temperature metals which could be melted down and recast and silicone rubber molds were developed. The normal cure process requires these molds to be placed in a pressure vessel and held at 500 psi for 16 hours to eliminate voids. The silicone rubber molds allowed the substitution of a 5 to 10 minute centrifuging immediately after pouring to displace the bubbles, then cure in a simple temperature chamber instead of a pressure chamber for 16 hours. Another approach involved the use of aluminum molds of simple construction which would allow the encapsulation material to be introduced under vacuum and pressurized at 500 psi, then the mold would be disconnected and placed into the temperature chamber. Each mold was its own pressure vessel. For high production rates using technology in other industries, a liquid injection mold (LIM) process (Figure 6) was investigated for both the dual coil conductor and the toroid. Acceptable parts with a minimum of hand labor—very consistent in quality—were obtained, but the production rate was limited by the long cure time of the Epon-825/HV hardener used. A material with a faster cure time meeting all of the other parameters required would greatly enhance this method of encapsulation.

Automatic mixing and metering equipments were investigated and typical equipment obtained to evaluate operation in low-to-medium production operations. This would substitute for the hand labor usually used in mixing up batches of encapsulation material prior to pouring. The equipment evaluated allowed the resin and hardener to be maintained under vacuum and introduced

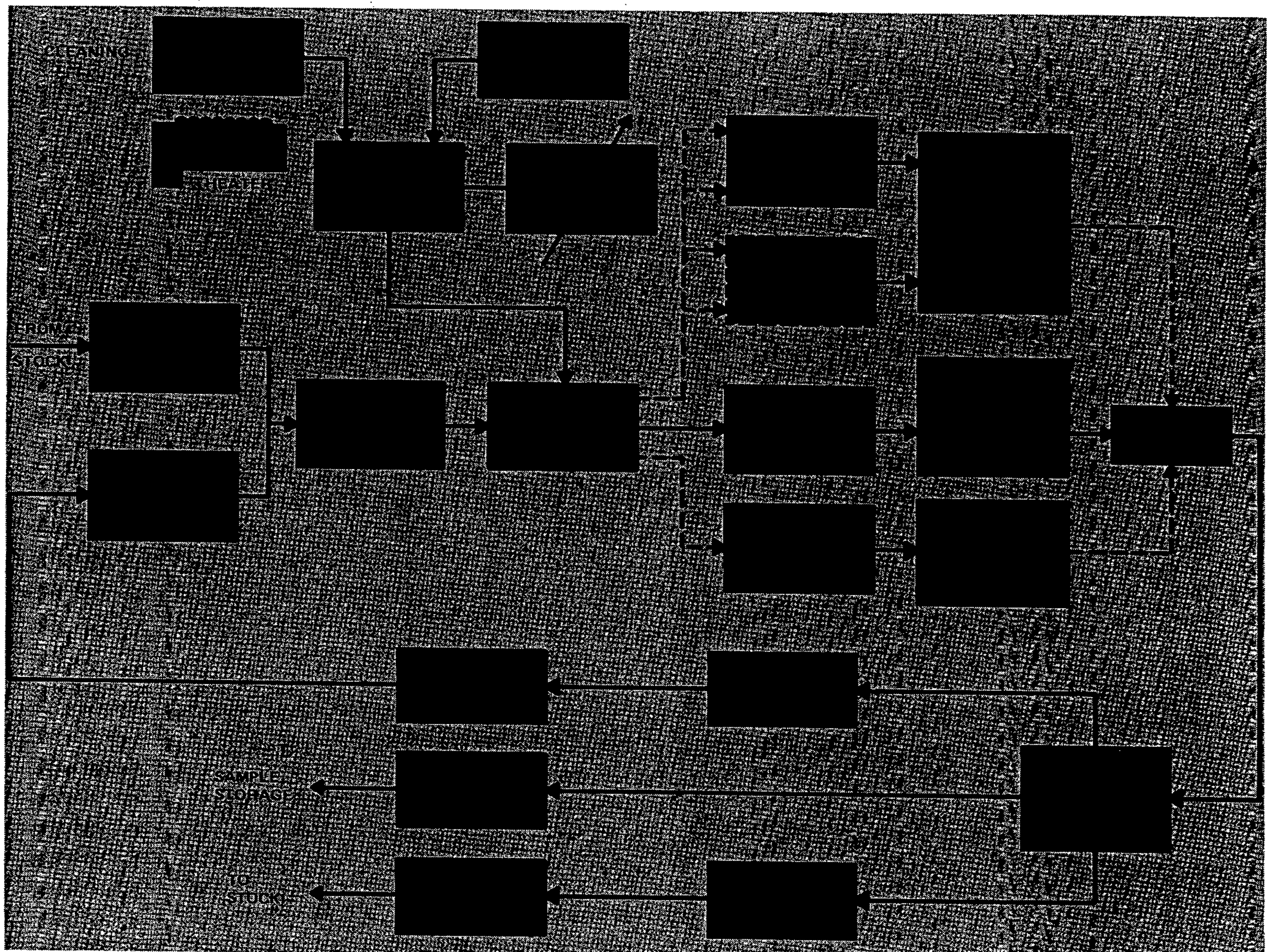


Figure 6

into the mold through a mixer which caused mixing to take place at the point of entry. Temperature blankets allowed the materials to be maintained at a high temperature to facilitate pouring by reducing the viscosity.

Structural Parts

Structural parts investigated included four areas as follows: shielded bobbins for high voltage transformers; thermoplastic and thermosetting plastics for coil supports; anchoring of windings within transformer coils; and C-core assembly techniques. The use of fine and ultrafine wires in high voltage windings increases the maximum voltage gradients in the encapsulation materials. Controlling the spacings of such wires which have high voltage differences is difficult; consequently, the use of electrostatic conductive shields (Figure 7) is employed in the construction of the bobbin. A typical high voltage bobbin will have a low potential or ground electrostatic shield on the outer surfaces with an insulated, but also conductive, shield on the inner surfaces where the high voltage winding is located. In this manner, location of the separate wires is not critical in controlling the voltage gradients being developed. Also, a modified bobbin was designed (Figure 8).

In high reliability transformer design, thermoplastic materials are rarely used because of their tendency to

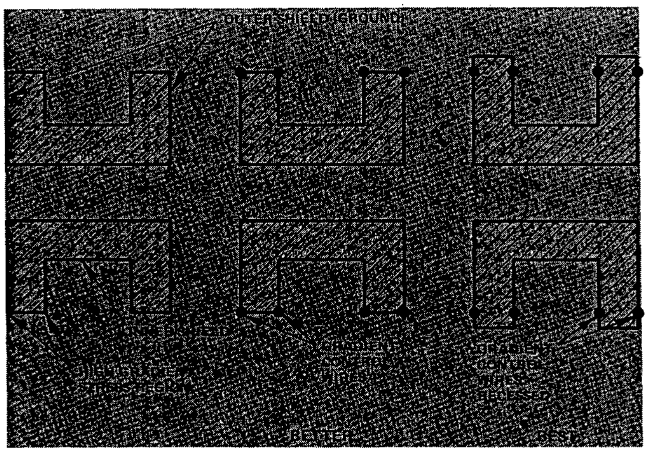


Figure 7

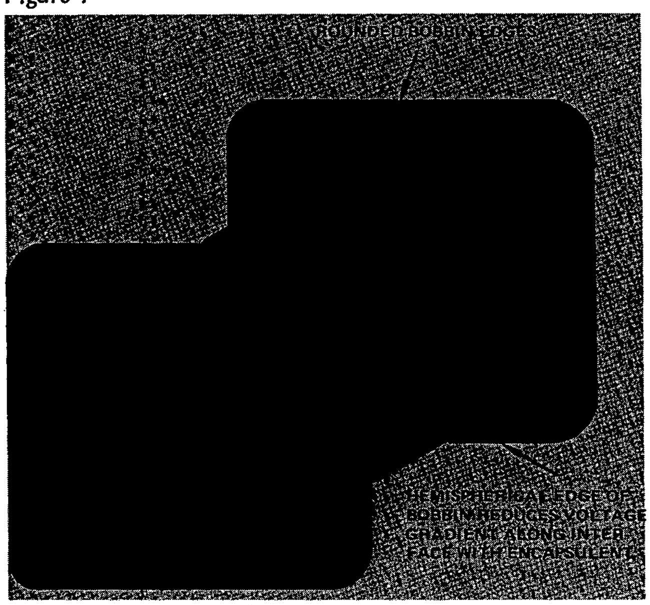


Figure 8

soften at the higher temperatures to which the component is subjected, either during testing or actual operation. Some of the newer high temperature thermoplastic materials such as Ryton (which has a softening point in excess of 525 F) were evaluated. Typical square bobbins of this material were obtained and windings made. Another requirement in the specification was that no softening of such thermoplastic material would occur when the terminals swaged in it would be soldered to. This was not found to be possible, as the softening could not be prevented by any acceptable soldering technique. The problem could be eliminated by a pulse type welding, but this seemed to add additional complications which overshadowed any advantages of using thermoplastic materials.

Non-Tape Alternatives

It is accepted practice to use small pieces of mylar tape to anchor windings at the end of each layer or at various stages during the winding operation. The presence of such tapes in a winding provides stress points in the encapsulation which can cause it to crack under thermal cycling, the possibility of entrapped air producing voids at critical parts in the winding, and a lack of adhesion of the encapsulation material to the tape itself. To provide an acceptable method of anchoring windings without using tape, several quick setting adhesive materials were investigated. These included hot-melt, ultraviolet curing, and anaerobic types. It was found that these provided an acceptable substitute for the tape once the operator became used to the technique.

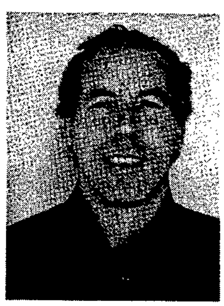
Conventional banding operations of C-cores assembled into windings on bobbins or sticks (which have already been encapsulated) use a metal clip and a soldering operation to anchor the band. By means of welding an auxiliary pull tab on the band, a method of welding was developed which required no clip and no soldering. The pull tab and excess band lengths are then cut off after welding, resulting in a low profile of only twice the thickness of the banding strap material.

Implementation

Part of the implementation effort was the holding of a government/industry debriefing at Hughes-Culver City. The purpose of this meeting was to give to all attendees an overview of the information assembled during this 2-year MM&T program, to note the major findings, to point out possible breakthroughs in reliability improvement, and to review new technologies. It is hoped that this presentation encouraged those who attended to delve into the complete final report for the entire story. Hopefully appropriate portions of this technology will be implemented into other operations so that higher reliability, lower cost electromagnetic components for missile systems, space projects, and commercial applications would be forthcoming in the immediate future. If this is done effectively, a quantum jump in component reliability and cost reduction will be obtained which will benefit all concerned.

Possible Via Holograms

Testing Aspheric Lens Surfaces



WILLIAM A. FRIDAY is a Research Physicist for the U. S. Army Missile Command at Redstone Arsenal, Alabama, where he has been actively involved with the development of the technology base for high energy laser weapon systems. He has acquired experience in laser optics, laser beam control, and laser/materials interaction. He has worked for the Missile Command for the past 20 years, while earning B. S. and M. S. degrees in Physics from Mississippi State University and the University of Alabama in Huntsville.

The U.S. Army's manufacturing methods and technology effort has been instrumental in creating one of the world's most unique facilities for the use of American industry. The National Hologram Facility at Billerica, Massachusetts came into existence due to a mantech project funded by the U.S. Army Missile Command in its quest for a method for testing the surface accuracy of deep aspheric lenses. During the course of this project, which was carried out by Aerodyne Research, Inc., investigators turned to the computer to calculate and draw holograms that could be used as references for the testing of production lens surfaces. The achievements of the project will have impact for years to come in the field of design as the facility is made available to other U.S. Government contractors.

Simulation of not only the image but also the location of individual segments of the developing hologram plays a key role in making the system practical. The speed and location accuracy of mechanical devices during scanning were inadequate, so cathode ray tube imaging controlled by computer generated data points simulates the position of each succeeding segment in building the total holographic image.

Aspherics Pose Problem

The use of computers to calculate and draw holograms of objects or wavefronts that exist only as a concept in the mind of the designer is a technology that has been explored for many years by a number of researchers. Among the applications shown feasible are©

- Interferometric testing of deep aspheric lenses
- Recognition of spatial, spectral, or temporal patterns by computer optimized hologram filters
- Synthesis of three dimensional views of nonexistent objects for CAD/CAM
- Production of light, large, and efficient optical elements for all wavelength ranges
- Coordinate transformations on input images
- Duplication of optical hologram functions with better process control.

NOTE: This manufacturing technology project that was conducted by Aerodyne Research, Inc. was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Directorate for Manufacturing Technology, DARCOM. The MICOM Point of Contact for more information is William A. Friday, (205) 876-8611.

Yet, despite the promise, computer generated holograms (CGH's) had not been applied widely outside the laboratory. The techniques to design the holograms were well developed, but writing them to sufficient accuracy proved very difficult.

In 1979, personnel at the U.S. Army Missile Command realized that holographic testing could be the key to testing the diamond turned aspheric optics the Army required. By diamond turning they could produce aspheric metal mirrors with almost arbitrary shapes; yet they had no way to verify the shape of the optics thus produced. Spheres and flats are tested routinely by optical interferometric comparison with reference spheres or flats, which can be produced to very high accuracy. But when the asphere deviates too dramatically from any reference sphere, the interferometric method breaks down—fringes become unresolvable and information is irretrievably lost. What was needed is a perfect reference asphere. But how would such an asphere be recognized even if it was produced?

The answer, known for many years, was to create by computer holography a light pattern (wavefront) appearing to come from the perfect reference asphere. Theory held that a hologram writer should write at least 40,000 points in each direction and have point location accuracy of at least one part in 40,000. No such writer existed at that time.

MICOM personnel set out to produce a suitable "holowriter" and make it available for all U.S. Government contracts. Accomplishing those goals would make writing adequate computer holograms easy and inexpensive.

In July, 1982 at Aerodyne Research, Inc. in Billerica, Mass., a practical holowriter constructed under MICOM direction was demonstrated. The holowriter is now in place at Aerodyne under the ownership of the Rome Air Development Center at Hanscom AFB, Bedford, Massachusetts. It is operated under contract at Aerodyne for the government and can be used in support of any contracts with the U.S. Government. The specifications achievable include

- Up to a 7 cm x 7 cm format
- Lines as small as 5 micrometers
- Absolute location of the center of each line to within 0.15 micrometers.

The 7 cm (70,000 micrometers) dimension at 5 micrometer resolution leads to 14,000 lines. The locational accuracy is one part in 4 x 10^5. Both of these numbers are comfortably greater than the minimum described earlier and much greater than prior art.

Basic Scheme

The basic scheme undertaken was to

- Use an ultra-low distortion CRT (greatly demagnified) to write a small, square portion (cell) of the hologram onto a photographic emulsion on an ultraflat photographic plate
- Translate the plate to write the next cell
- Measure the translation to an absolute accuracy of 0.1 micrometers interferometrically
- Write the next cell on the CRT face with position chosen to compensate for the unpredictable (to within a few microns) stopping position of the stage.

Of course, such a system had to be computer controlled. Achieving meaningful 0.2 micrometer accuracies required extremely careful engineering as well as the use of a temperature controlled room.

Figure 1 shows the overall system layout schematically. At lease a dozen factors converged to make improvements beyond the existing performance level very difficult and very expensive. A few of those factors follow:

(1) The special right-angle mirror required for the 2-D, orthogonal interferometry cannot be made much longer without itself introducing 0.1 micrometer errors;

(2) The writing time for a 10^6 x 10^6 hologram approached a full working day, and system stability for longer exposures was doubtful (to say nothing of latent image failure);

(3) Only one commercial photographic plate exceeded minimum requirements on sensitivity, resolution, and flatness even with the current (1979) design;

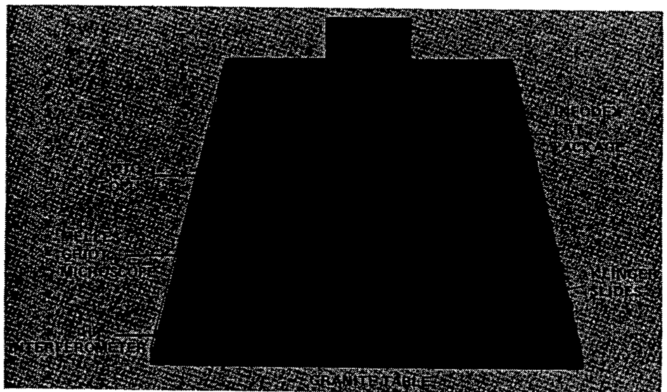


Figure 1

(4) The demagnification already was so great that it, not depth of focus, required the use of state-of-the-art controllers of lens-plate distance;

(5) Temperature gradients (beyond those already sensed and compensated for) as well as temperature drift limited mechanical measurement accuracies to no better than about 0.15 micrometers;

(6) Temperature variations within the room limited the CRT demagnification to roughly current values.

Hologram Encoding

Investigators chose to write binary holograms with continuous fringes and to achieve a 50% duty cycle for all fringes. The basic cell is shown in Figure 2. It is a square cell even though system asymmetries give it 2000

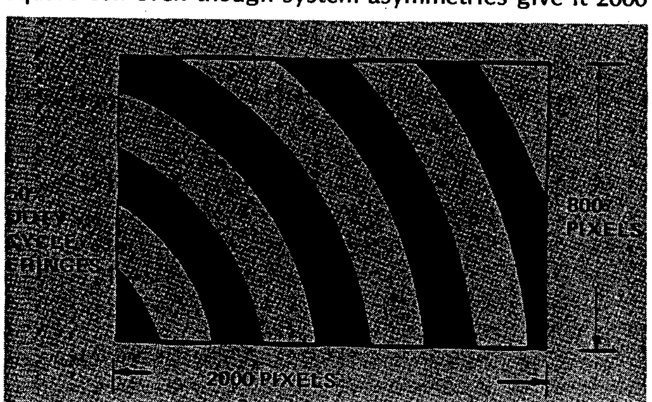


Figure 2

horizontal but only 800 vertical pixels. As will be seen, the fringes will be predominantly vertical, so phase accuracy is controlled by the 2000 pixels while the 800 pixels simply allow for the slow bending of the fringes. The minimum fringe to be written is 4 micrometers, but its center can be located within 0.15 micrometer.

To calculate the exact fringe values at $10^6 \times 10^6$ points even at the incredible rate of one microsecond per point would have taken months. Obviously, some shortcuts had to be taken. To help find fringe centers, a priori knowledge was utilized that the fringes are:

- Largely vertical
- Nonintersecting
- Continuous.

With the fringe centers investigators could get local fringe spacing and hence know the fringe width necessary to give 50% duty cycle. With their a priori knowledge that the fringes were largely vertical, they were safe in not calculating fringe centers at each possible vertical position. The calculation of fringe centers used the Secant method, with the starting guess made on the assumption that the next fringe spacing equals the previous one.

Quibbles

Two objections to computer holographic testing of aspheres can be made:

(1) The wavefront produced is accurate only modulo λ (the wavelength for which the hologram was designed). This, of course, precludes multiwavelength testing. In addition, this creates optical path differences which preclude testing with sources of too limited temporal coherence.

(2) The hologram design is based on optical path differences which are calculated by computer ray tracing of the interferometer system. Unless the system (particularly its lenses) is known to great accuracy, users can easily produce the wrong wavefront by designing the hologram for an interferometer not available. There is no way to avoid this problem in any testing method (holographic or nonholographic).

DESIGN CONSIDERATIONS

Designing the holowriter required the careful selection of components and equally careful attention to the environment in which those components had to function.

Temperature of Room

The primary effect of changing room temperature is to change the physical dimensions of all the metal components, bases, and supports. Listed below are some of the ways those dimension changes can be expected to cause problems:

- The demagnification factor may vary because the object distance and image distance (relative to the principal planes of the microscope) may change as the basic structure shrinks or expands.
- The lateral position of the optical axis of the microscope may change relative to the CRT and/or relative to the stage.
- The separation between the interferometer and the mirror it is measuring may be due partially to mirror motion and partially to temperature induced changes in system (e.g., baseplate) dimensions.

There are only four ways to combat this problem: (1) design in temperature compensation, (2) minimize temperature change, (3) use nonexpanding materials, and (4) measure temperature and correct for it.

Compensation means using the known expansion coefficients of different materials to design counteracting temperature effects. This was used, for instance, in keeping the microscope axis properly aligned with the support system.

Temperature "constancy" was achieved by building the system in a temperature controlled room. Most heat sources (except the CRT) also were kept outside that room. With temperature considerations, the questions are: how stable is the temperature over the anticipated writing times and how big are the temperature gradients?

Low expansion materials (e.g., special ceramics) were seriously considered for the baseplate and other major structural components; however, cost and inconvenience ruled them out.

Measure-and-compensate methods are used to correct the interferometer readings for the effects of temperature gradients.

When effects of all the tradeoffs and compensations are combined the conclusion is reached that the lateral accuracy depends on the total temperature excursion during the total writing time. Time enters in as a further drift problem. Thus, there can be a drift in the reference to which the room temperature is compared. This is not believed to be significant during any one working day.

In a more expensive system of the future, significant improvements could be obtained by using

- A temperature controller with greater stability
- Low expansion ceramics wherever possible. This could lead to roughly a factor of two improvement.

Stage Motion

As the stage micrometers are driven, the stage itself undergoes periodic up and down motion from the gear drive. This motion is certified by the manufacturer to be ± 1 micrometer. The primary effect is not on focus (our depth of focus is around 25 micrometers) but on the demagnification ratio.

When attempting to drive the stage to a new position, a location is arrived at that differs from the target position by unpredictable errors. These errors are the settling errors certified to be roughly 10 micrometers. The approach to dealing with these errors is to write the CRT image laterally displaced from the center. The demagnified image is then automatically centered.

Photographic Plate Choice

The photographic plate had to be extremely flat to achieve good resolution because of the previously noted demagnification effect. Kodak offers the flattest available photographic plates (Microflat©).

In photographic emulsions big grains are used to gain high speed. Because high resolution is required, low speed must be expected. Lower speed means longer exposures. Longer exposures mean less resolution. Clearly, there is a narrow "window" in the set of all emulsions which satisfies a mutually consistent, useful tradeoff between speed and resolution. Of the few potentially interesting emulsions, only one was available on

Microflat plate. It was concluded that this was the only commercially available photographic plate suitable for use with this hologram writer.

CRT Choice

The CRT choice was dominated by considerations of speed and distortion. To avoid writing the hologram a point at a time, investigators chose to write it a square cell at a time. The speed improvement factor in so doing is the number of points in the cell. The ultimate speed, of course, would come from writing the whole hologram at once. For the number of points and for the positional accuracy required, this ultimate CRT does not exist. The question then is how large a cell (in terms of number of resolvable elements) can be written to required accuracy. The original objective was to write fringes to $\lambda/100$ accuracy. With a fringe period of 10 micrometers this requires 0.1 micrometer on the hologram. On the CRT it requires $\rho/50$ accuracy across the cell, where p is the width of a single point. That is, the cell needs to be confined to that region of the CRT giving less than 2% distortion. For a bad CRT the cell may be very small. For the best CRT, it may be very large. For the good and affordable CRT the Infodex PD1200M34 with a 12 cm diameter RCA C82200 ESI tube was chosen. The usable area was 5 cm x 5 cm for this project.

The image must be "on" long enough to expose the emulsion. It must be bright enough so that retrace is not required to achieve the desired exposure level. The phosphor decay time should be less than the time needed to step the stage and let it settle to within 0.1 micrometer. For this system that time is 0.17 seconds. The decay time for the RCA tube phosphor is 0.001 seconds.

The chief obstacle to better CRT performance (bigger cells) is cost. The next best CRT was roughly $5,000 more than the one bought. In a program in which cost was a prime consideration, this was not a difficult option.

Mirror Design

The right angle mirror attached to the stage to allow stage x-y position monitoring must be locally flat to allow the interferometer to function. In addition, it must be accurately 90 degrees in order to not couple x and y measurements. If it were exactly 90 degrees, the mirror could be aligned at $x=x_0$ and mirror alignment could be adjusted so that the x indication is constant to better than 0.1 micrometer regardless of y. The test is to move to a much different value of x and scan y there. It should again lead to "constant" x.

It follows that investigators cannot expect to avoid correcting x according to y—i.e., calibrating the mirror and storing a simple correction factor for use by the computer.

Vibration

In a system designed to approach 0.1 micrometer positional accuracy, normal vibrations would be catastrophic. Four precautions were taken to minimize vibration. First, an air-suspended table was used to isolate the system from normal slow vibrations (people walking, machinery operating, earth settling, etc.). Second, a granite table was used to damp fast vibrations. Third, only heavy, solid components were used. Fourth, holograms were written only after disturbances from stage motion and disturbances from human operators had time to dampen out.

Air Currents

The temperature controlled room continually circulates air. This should maintain the desired temporal and spatial uniformity, but it can also cause sufficient turbulence to cause misdirection of the writing beam. Turbulence spoiling shields were built to remove this problem.

Interferometer

The interferometer was one of the easiest choices. What was sought was

- Resolution of 0.1 micrometer or better
- Reading speed sufficient to verify damping of stage motion relative to stage settling time.

The standard of the industry is the Hewlett-Packard interferometer chosen. It is more than adequate on both counts.

Radio Frequency Interference

Radio frequency interference (RFI) was anticipated that would present a problem for delicate display circuitry and so investigators tried to shield the environmentally

controlled room against it. It turned out that RFI also affected the controlling PDP 11/23 computer. After much effort, this and a line surge problem caused by the room environmental controls were brought under control.

Information Flow

Two primary tasks were needed to be accomplished by computer:

- Calculation of the hologram (a nontrivial task in that the writing beam must be fed information to 0.1 micrometer accuracy over an 8 cm diameter hologram for a total of about 5 x 10^6 bits)

- Control of the writing (move the stage, sense stage position, write the cell, decide next cell position, obtain cell data, etc.).

In principle, one computer could do both tasks. In practice, this proved far too expensive.

To operate the holowriter at its design speed while making fringe calculations on the fly, Aerodyne's PRIME computer would have had to be devoted full time to the task (all other users banned for the entire writing time). The financial burden to the program of this operation would have been immense. Instead, it was chosen to split the tasks between two computers by providing a dedicated PDP 11/23 to control the holowriter. The primary cost (in time, inventiveness, and dollars) of this approach was that an interface between the computers had to be designed and built and a 100-foot special cable had to be designed and installed to connect the computers. A simplified task division is shown in Figure 3.

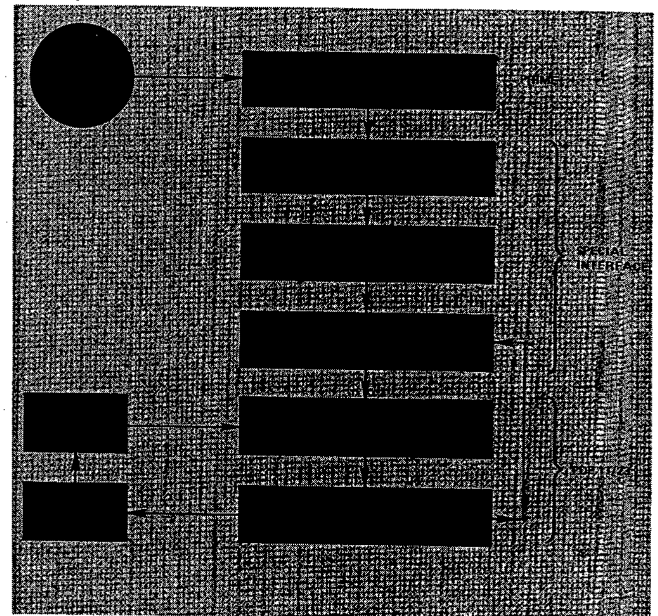


Figure 3

SYSTEM DESCRIPTION

Having described the system philosophy, the system components, and the system design parameters, the system is now described as a whole. In a sense, the system was designed once the components were selected. Unfortunately, most of the hard work went into assembly and integration.

System Appearance

The CRT, mount optics, stepping motors, and interferometer were located on an air suspended granite table in the environmentally controlled room. The room environment is set, controlled, and recorded, and two entries to the room are locked during hologram writing. The room had to have all light leaks plugged and all control lights covered because the plate is panchromatic and is exposed for a multi-hour period. All manual manipulations after the plate is removed from the box are done in darkness using an infrared viewer. Outside the second door of the primary double chambered entry way is the PDP 11/23 and associated I/O equipment. The operator controls all operations from there. Down the hall is the PRIME computer used for the fringe calculations and the interface based on the PRIME/RAMTEC interface which was already designed for rapid data transfer from the PRIME.

Alignment, Magnification, and Focus

Plates are inserted in the dark (as noted above) and kinematically located within the plate holder. The location of the first fringe is selected by the starting point on the micrometers on the stage motion transducers. The magnification can be "trimmed" electronically. By exposing square cells (which ought to abut perfectly) on a test plate while changing magnification between

cell exposures, agreement can be achieved between the cell size on the plate and the interferometrically controlled stage motion. Thus, the scale of the cell can be accurate to interferometric accuracy. Focus can be obtained through direct observation of backscatter through the pellicle beam splitter. It has proved satisfactory in practice to

- Align the plate holder apparatus once optically so that no focus change occurs over the whole plate
- Measure the air gauge gap indicator reading
- Use the air gauge to reset the focus for new plates (the microscope must be elevated and reset in the dark to insert a new plate).

Operational Notes

The center (low distortion) part of the high-quality television tube (Infodex) is used to write a 5-cm square cell. This is demagnified by a factor of 250 onto a Kodak Microflat© plate bearing a holographic emulsion. The resulting 200 micrometer square can contain up to 40 lines (20 full fringes). After the first square is recorded, the system is stepped to the next nominal position 200 micrometers away. Of course, the stage will not settle to exactly where it should. A two-axis interferometer reads the actual stage position to within 0.1 micrometer.

Readjusting the stage position is too slow, so the next cell is drawn so displaced on the TV face that it is imaged perfectly abutting the previous cell. The TV cell image, being nonmechanical, can be adjusted in position much faster than the mechanical stage. Speed is important, because it takes 122,500 of these cells to form a full 7 x 7 cm hologram. The holowriter completes the task in about 10 hours.

Each hologram is annotated automatically and is given precisely placed fiducial marks to allow accurate positioning.

Because there are severe problems with stability, vibration, temperature drift, and humidity changes, the holowriter is designed to compensate for these effects and is placed on an air suspended granite table in an environmentally controlled room.

Final System Specifications

Table 1 shows final system performance levels.

Parameter	Value
Hologram Size	7 cm x 7 cm
Fringe Size (minimum)	5 micrometers
Absolute Location Accuracy	0.15 micrometer
Writing Time (full format)	12.5 hours

Time Budget for One Cell

Table 2 shows the time required for the various operations.

Operation	Time (milliseconds)
Step	170
Expose (2 traces)	100
Total	270

Sample Rulings

Figure 4 shows a magnified area covering several cells. This illustrates the accuracy and quality now achievable.

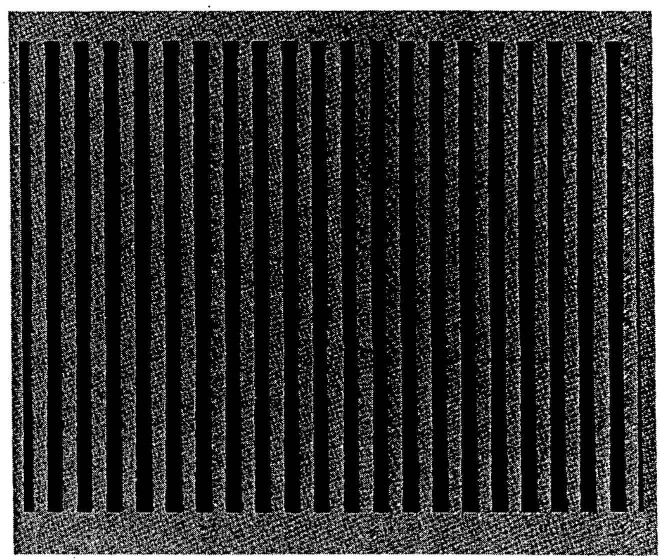


Figure 4

USER NOTES

Hologram Design

The user must supply

- Best fit polynomial coefficients for the phase function (measured in wavelengths with the maximum radius, ρ, equal to 1).

Higher orders are easy to handle but normally unnecessary to achieve desired accuracy levels. To achieve $\gamma/20$ accuracy, equations should differ from the computer calculated patterns by at most 5%. The user then supplies

- The tilt angle
- The maximum radius (corresponding to $\rho = 1$)
- The wavelength.

Sample Run Made

A simple case was run to show the workings of the program. None of these parameters were realistic, but were intended to give an interesting output plot. The system says that the maximum number of cells (along the hologram diameter) is 10. It also says that there are 60 fringes across the hologram. Figure 5 shows a plotter version of the magnified hologram. Each of the small rectangular cells that makes up a fringe should be black (and it is on an actual hologram). Points within these cells all have the same horizontal displacement, because investigators elected not to calculate every vertical line but, instead, to calculate only every Nth/ line. In this case N = 10. This gives a factor of N increase in the calculation speed and need not cause any measurable errors. The top and bottom rows are barely intersected by a $\rho = 1$ circle, so the system extrapolates straight fringes outside $\rho = 1$. The artifacts at cell "seams" stem from the fact that the plotter is not as accurate as the holowriter. Note the 50% duty cycle fringes across the whole hologram. This is one of the unique features of the Aerodyne computer design software, which leads to a uniform diffraction efficiency across the hologram.

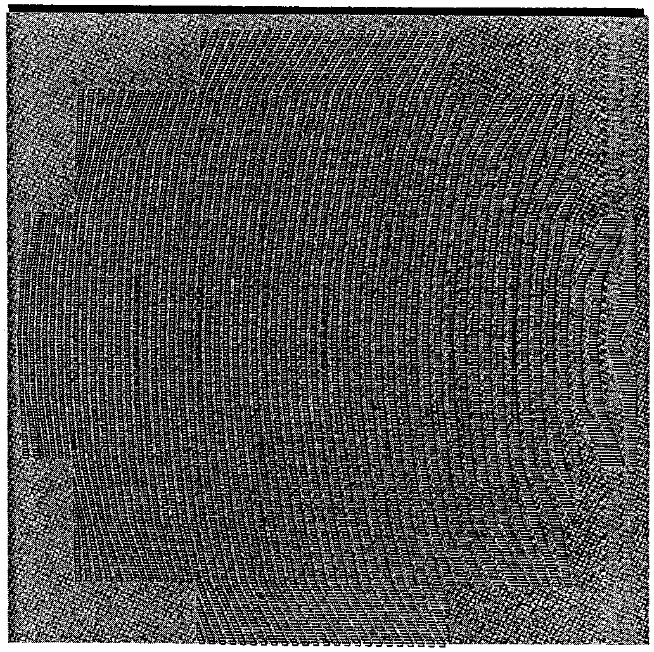


Figure 5

Calculating the Hologram

The PDP 11/23 computer that operates the system must provide precisely 2.06 x 10^{11} bits of information to the holowriter. Calculating and handling this amount of data at roughly megahertz rates is a formidable task. The National Hologram Facility has written special hologram design computer programs for testing aspheres and for general-purpose Brown-Lohmann holograms.

Future Uses

The CGH equipment is now available to many users at reasonable cost (charges cover only labor, materials, computer time, and maintenance). Wavefronts produced from CGH's are easily copied optically to produce thick, efficient wide splitting angle holograms. CGHs can be copied onto photoresist for metalization or other treatment, leading to long wavelength (e.g. 10.6 micrometer) holograms. The possibilities are now limited only by user ingenuity.

New System Versatile in Production

Modular Device Tests Electro-Optic Components

by

William A. Friday
U. S. Army Missile Command

(See "Testing Aspheric Lens Surfaces"—p. 18)

Testing of electro-optical components has been advanced to a much higher state of sophistication by the U.S. Army Missile Command as a result of two companion MM&T projects that the command has sponsored. This article discusses the problems inherent in optical system design and presents the methods developed during the project to surmount these difficulties. The project developed a high-speed automated lens tester which measures focal length, modulation transfer function, defect location, and surface scatter. The effort was companion to a manufacturing technology project described in another article in this issue in which MICOM sponsored development of a computer generated hologram writer to test deep aspherical lens surfaces.

Under the MICOM MM&T contract, a modular device was designed and built by Science Applications, Inc., for optical components and systems. The system allows testing of a wide range of diameters—afocal or focusing, transmissive or reflective elements—and complete systems of any complexity with appropriate tailoring of input and output wave fronts. The system is designed for a production environment to provide high sampling rates with data collection and analysis complete in a few minutes per element.

Overspecification A Problem?

The design of an optical system requires more than an understanding of the theories of geometric and physical optics. There is a technology of component and subsystems production that must be dealt with. Otherwise, the resultant optical system may well be inefficient, too expensive, low performance, or all three. The U.S. Army,

NOTE: This manufacturing technology project that was conducted by Science Applications, Inc. was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Directorate for Manufacturing Technology, DARCOM. The MICOM Point of Contact for more information is William A. Friday, (205) 876-8611.

in its absolute need for high performance and reliablity, felt that it might be overspecifying and perhaps incorrectly testing electro-optical devices. If so, it might well prove to be spending more money than required. Additionally, it might be forcing vendors to supply designs that were weight or size inefficient. Furthermore, it becomes a matter of suspicion that the optics, being the very front end of a seeker missile, should amost always be designed first, not last.

Once an optical system is decided upon, the spatial requirements and the component interrelationships are not very flexible. Unfortunately, it is not at all uncommon for project developments to let the optics take a back seat. Perhaps this is because optics is so mature a field of science that it is taken for granted that it will not present the problems expected of aerodynamics and microelectronics. However, it should be pointed out that it is far simpler to modify a breadboard circuit to "tweak up" its temporal frequency response than it is to improve the spatial frequency performance of a lens or mirror.

Parameter Specification

One would hope that optical component and assembly specifications would be based on a clearcut understanding of what happens to overall system performance if some parameter is changed. In the case of an optically guided missile it would be hoped that the influence of increased scattering, for example, on the acquisition and accuracy of the seeker would be known. In fact, the investigations of this study showed it not so. As this circumstance became clearer during the program investigations, an avenue was sought by which such information might be obtained. In effect, it was found that the area of investigation needed to be extended from the area of concern initially proposed.

With this objective in mind, discussions were undertaken with the U.S. Army Missile Command's Guidance and Control Directorate. In particular, the G&C facility for hardware-in-the-loop captive sensor simulation of homing missile flights was visited. This facility is designed for low cost statistical analysis of miss distances for laser spot seeking missiles. Figure 1 shows the basic arrangement by which a seeker head is strapped into a multiaxis motor driven gimbal and a laser spot is rear projected onto a screen. Digital and analog computers are used to calculate aerodynamic effects and to cause laser spot displacement and gimbal motion in simulation of the missile's closure on a target. At the end of a run, the miss distance is output. Statistically significant data can be compiled since large numbers of runs for various acquisition ranges and angles can be made at low cost.

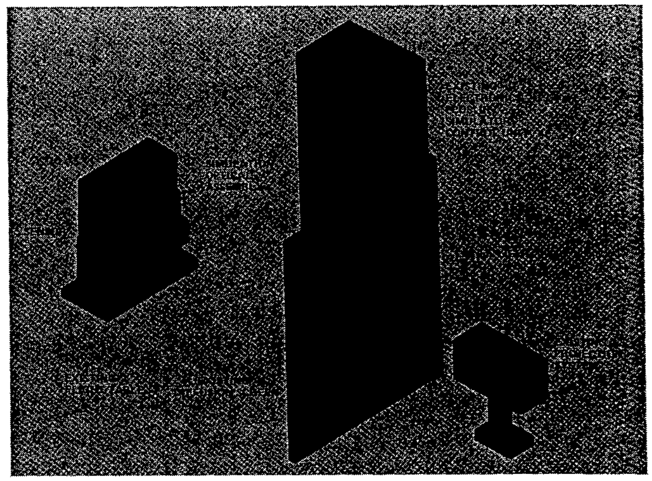


Figure 1

It was suggested to the facility director that an optical seeker assembly be made available for modification to its optical components. These modifications would be made in a controlled manner and categorized by the proposed automatic testing facility. In this way, a large amount of system performance data could be compiled by multiple runs of the sensor after each modification. The resultant data would be unprecedented and would, perhaps for the first time, lead to seeker component specification based on something other than educated guesswork.

OTF Gives Best Measurement

The contractor has examined production testing as it relates to tactical electrooptic homing missiles and suggests that the optical transfer function and scattering measurement concepts are basically both sound and applicable. The U.S. Navy at China Lake, California, is active in investigation of scattering phenomena and measurement.

The contractor concluded that simple adaptation of the many scattering measurement optics would be adequate for seeker and designator optics. A similar situation exists in optical transfer function (OTF) measurement except for the fact that the techniques and explanations of OTF, derived from electrical engineering practices, are only a partial adaptation. Everyone seems to understand the "big picture" or idea of OTF at the component and assembly levels, but few in the optics community are able to address its details on a practical level. Accordingly, the con-

tractor's work was concentrated on this area. This included efforts to interact with project offices and to communicate their activities with the optical community at large. The optics community is making some progress toward adopting the pragmatism of Project Offices by organizing a group (which includes the contractor) to arrive at specification via consensus standards.

Two categories of testing have been delineated by practical applications over the years. One category is particularly suited to in-process measurement while a single component is under fabrication. This category uses interferometric techniques to determine surface figure. However, once a component has been completed, it is best tested with regard to result system performance. This generally involves measurement of spectral efficiencies, scattering coefficients, and spatial resolution.

Traditionally, the spatial resolution has been given in terms of limiting resolution. However, it was recognized that two systems could have the same limiting resolution yet have very different system performances. This results because limiting resolution implies specification of performance at a single spatial frequency. In practice, complex optical arrangements can include aperture shapes, obscurations, and detection techniques that rely on spatial frequencies less than the limiting resolution. It is possible for an optical assembly with better limiting resolutions than another to actually give poorer system results if lower frequency components are important, as often is the case.

The most meaningful attempt to improve the appropriateness of component performance in an assembly grew out of linear systems theory and Fourier analyses. This is the approach most meaningful to evaluation of missile seeker optics. This approach is generally termed optical transfer function (OTF) analysis (Figure 2).

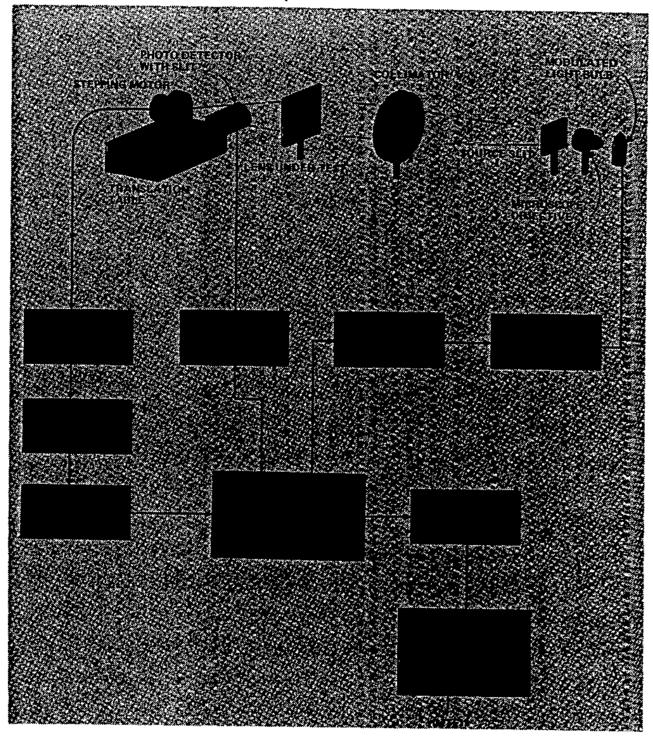


Figure 2

Transfer Function Theory Practical

Despite rapid growth in the field of optics during the late 1960s and the 1970s there is still a widespread acceptance of the criterion known as resolution. For many years the classical method of assessing image quality has depended upon the measurement of the limiting resolution of the particular system under evaluation or of the system and film combination. This type of test can have the advantage of including the detector, as for instance in the photographic resolution testing of a lens to be used for photography or the visual testing (by observing adjacent stars) of an astronomical telescope.

The tests are tedious to perform and must be carefully controlled to be meaningful. Therefore, the information that they provide is of little use for anything other than determining the limiting resolution of the system. Even so, the measurement must be extremely questionable, particularly when the image is received on a screen or viewed in a microscope. In these cases the resolution may be limited by the coarseness of the screen or the available magnification of the microscope.

The tests themselves produce results that are of little use to the optical designer as a quantitative guide to modifying his design. In addition, the type of test object, usually a three-bar square-wave target, bears little correlation to an actual scene since it is neither a typical shape nor comprises a single frequency.

Despite the problems associated with resolution, only a few of which have been listed above, it remains obstinately in use today as a basis for manufacturing and evaluating optical systems. Only in the field of optical design has a more advanced terminology become universally accepted.

One of the biggest problems has arisen in the last decade due to the introduction of a wide range of new electronic imaging systems, which has considerably magnified the problem of specifying and designing optical systems for use with them. It was determined many years

ago, principally in the television field, that lenses with the highest resolution were not necessarily the best lenses for use with image orthicon tubes. As far back as 1948, the real key to specifying lenses and detectors in similar terms was discovered.

The establishment of a transfer function theory in optics, similar to frequency response in electrical circuits, provided the relationship that was required. For our purposes it is convenient to regard the transfer function merely as the relationship between the input and the output of an optical system. The theory utilized here was developed by many independent workers over the years and is based on a combination of electrical communication theory and optical diffraction theory. Because of the versatility and completeness of Transfer Function Theory, it has become a standard practice today to specify and design systems in these terms. This has demanded an understanding of the principles from a wide variety of disciplines—optical, mechanical, electronic, and chemical engineers for example.

Basic Imagery Principles

The quality of the image formed by an optical system is determined by three factors:

- Aberration in the optical system
- The wave nature of light (causing diffraction effects)
- Inaccuracies incurred due to manufacturing processes.

When the design is such that the aberration can be neglected (such as an f/2 lens stopped down to f/16) and errors of manufacturing are so small that they have no effect on the performance, then the quality of the image system is said to be "diffraction-limited."

Consider a lens system that forms an image of an incoherently illuminated narrow slit. In the ideal case, the distribution of light in the image would be an exact replica of that in the object. This can, of course, never be realized because of the finite wavelength of light.

If there is aberration present in the optical system, and in particular if the aberration is asymmetrical (as, for example, in a lens afflicted with coma), then the image is extremely complex. The intensity distribution in the image of a narrow, incoherently illuminated slit is known as the "line spread function" of the optical system forming the image. If the slit is replaced by a pinhole the corresponding function is referred to as the "point of spread function."

For the purpose of considering image formation, each point in the object can be thought of as a source, giving rise to a point spread function from different points in the object. This approach gives a good indication of the process of image formation but is not, however, the best approach toward designing and assessing optical systems.

A more suitable test object can be obtained by utilizing a sinusoidal intensity distribution. The image of a sinusoidal target always has a distribution that itself is sinusoidal. Behind this fact lies the whole basis for transfer function theory.

Consider a sinusoidal type target being used as a test object. In the ideal case, the object and image are identical, but since this, in reality, is never the case, the best we can achieve would be a diffraction limited image. The effect of diffraction is to reduce the amplitude. If aberration is present, in addition, the amplitude would be further reduced in the presence of asymmetrical aberration; the amplitude reduction is also accompanied by a phase change. If N is the distance between successive peaks of the target (in millimeters), the spatial frequency of the target is defined as 1/N-R cycles/mm. This is analogous to the familiar lines/mm term used for resolution charts. In the case of afocal systems, the units more frequently used are cycles/milliradian.

Modulation Transfer Function

An important property of the sinusoidal intensity distribution that we will utilize is the modulation. It will be noted that the mean luminance is taken high enough to bias the function such that the luminance is always positive. The modulation is often referred to as the contrast, but since the definition of contrast is not always the same, particularly in the photographic field, the term modulation will be adhered to.

Next consider a series of sinusoidal targets of varying spatial frequency but of constant amplitude. Later, as test objects, their images will be of reduced amplitude and the corresponding modulation can be calculated for each spatial frequency. If we define the modulation at zero cycles to be 1.0, a graph can be plotted of modulation against spatial frequency (Figure 3). This represents the variation of modulation with spatial frequency and displays what commonly is known as a "Modulation Transfer Function" curve, often referred to as an MTF curve.

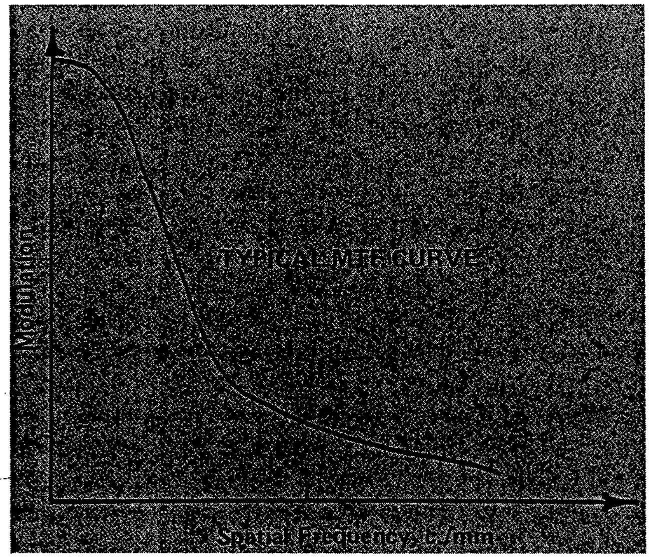


Figure 3

In the case of a lens possessing asymmetrical aberration or badly centered elements, the effect of the lens system is to cause not only a reduction in modulation but, as previously mentioned, this will be accompanied by a phase change. This phase change is dependent upon spatial frequency and contributes to what is known as the "Phase Transfer Function (PTF)." It is conveniently represented by the type of graph shown in Figure 4. Note, particularly, that this is a spatial phase shift and can only occur where the point image is asymmetric. Thus, in a centered optical system, spatial phase shifts occur only "off-axis" and for tangentially oriented lines. Radial lines will have no phase shift.

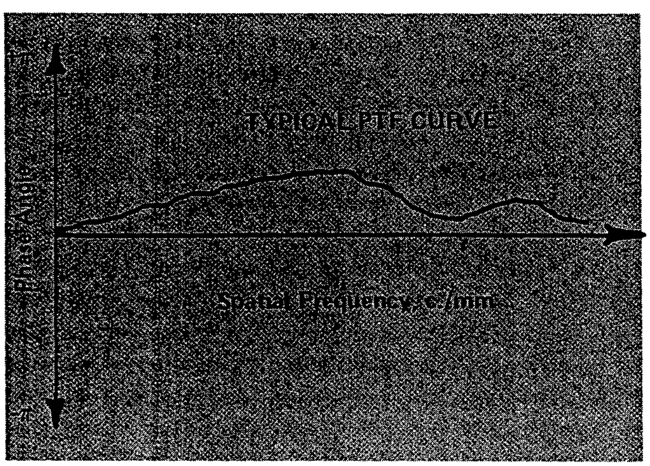


Figure 4

An interesting effect can be observed when defocusing a symmetrical lens, when phase shifts of 180 degrees can occur. This is consistent with visual observations when compared with the more common experience of observing the alternate bright and dark centers to the on-axis diffraction pattern as the system is traversed through focus.

Measurements of Modulation Transfer Function and the Phase Transfer Function combine to give what is known as the "Optical Transfer Function (OTF)" for the system under test. The OTF of a system can be obtained from the Fourier transform of the line spread function of the system under test.

Mainframe Configuration

All optical and electronic support hardware directly related to processing and control are located on the optical mainframe. The controller terminal including the data acquisition system, data storage, CRT keyboard assembly, and the line printer are remote from the optics mainframe. This division of the total assembly provides the user at the controller console with all necessary controls for system operation. All possible test functions are designed with automation in mind, therefore, the need for operator access to the optics mainframe is minimized.

The principal difference between the mainframe and a standard optical table is its three dimensional nature. For all practical purposes, a table is only two dimensional and an optical bench is only one dimensional (mirror adjustments excepted). Furthermore, standard tables and benches are not portable. The chosen mainframe is designed to be movable.

The mainframe concept is predicated on the recognition that repeated, detailed testing will be done on replicated components, assemblies, and systems. All tests, however, require standard elements. These are generally thought of as standard sources and detectors. In addition, there is an implicit wavefront standardization. Optical engineers commonly utilize either or both of two standard wavefronts: the plane wave and the spherical wave. The mainframe incorporates a collimator for converting a spherical wave into a plane wave.

In looking at the optics mainframe, a light path may be traced from the source assembly through a collimator. The path then proceeds to the test object. For the case of a transmission test system, the light path is traced to a detector assembly located behind the test system.

The design incorporates an off-axis parabolic reflector to provide greater flexibility in the choice of spectral range from 0.4 to about 14 millimicrons. More precisely, the

reflectivity is relatively flat over this range and effects of chromatic aberrations are eliminated.

Measured Optical System Parameters

The test facility is designed to perform specific optical tests at the system or component level. The measured parameters include:

- Focal length
- Optical transfer function
- Large area scatter
- Local scatter
- Spectral characteristics.

Depending upon the device being tested, a selection of tests is developed which adequately characterizes the system under its normal range of operating conditions.

After an optical component is mounted on the test jig, the focal length can be estimated to within 5-10 percent; testing will be centered about this estimate and the peak value then chosen.

Because the location of the principal plane may not be known, the focal length measurement is performed in such a way as to be independent of alignment reference to the principal plane. A translator on which the detector is mounted is moved perpendicular to the optical axis until the focal point is found. From this measurement, the focal length is computed. Focal lengths of both single components and complete systems can be found in this way.

The system layout for OTF testing is shown in Figure 5. A folding mirror reflects the source radiation onto an off-axis parabolic mirror for collimation. A four-inch-diameter beam is then directed onto the test component. The test assembly consists of a test block for mounting the optical component to be tested and two translators. The translators are used to position a pyroelectric detector for focusing and off-axis measurements. The entire test block is mounted on a rotor for scanning.

A diagram of the OTF process is given in Figure 6. The detector signal is first locked in by the automatic gain adjustment. The slit temperature is recorded from a temperature sensor located on the slit mount. The step size of the scan rotator is determined based on the focal length of the test component. A scan is made of the line spread function with detector readings synchronized to a 5Hz chopper signal. Readings are made and data sampled at the Nyquist rate for a 0.5Hz signal bandwidth corresponding to 100 lines/mm. The data is stored and then scaled spatially as necessary based on the focal length of the test component. The OTF is then determined from the line spread function data using the hardware processor. The results are processed for display and storage.

The system layout for scatter measurements is shown in Figure 7. The component to be tested is mounted on the test block and rotated into position using the scan

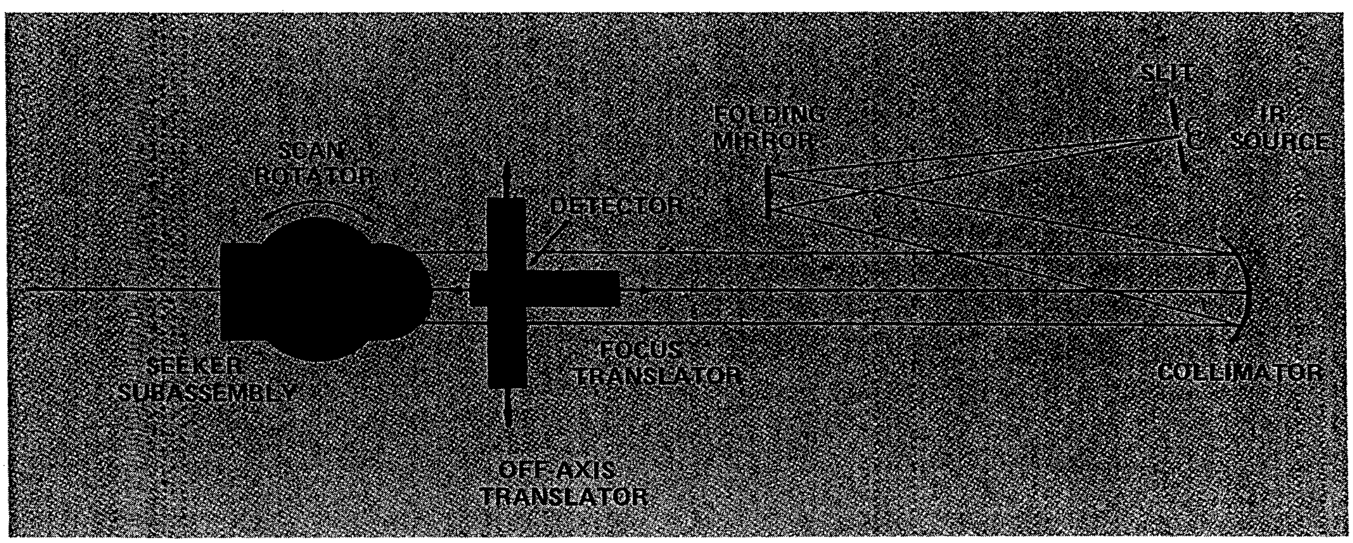


Figure 5

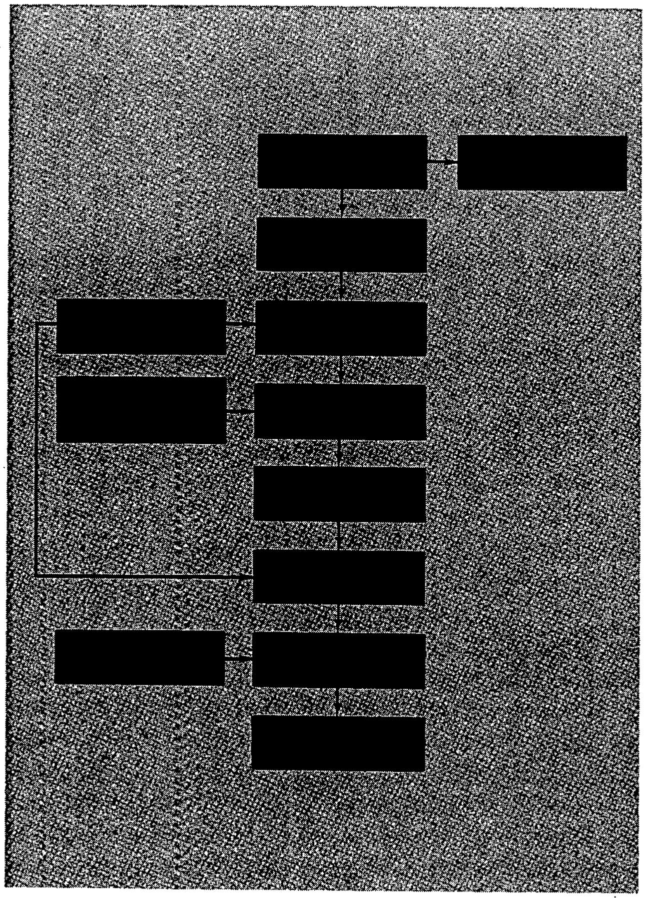


Figure 6

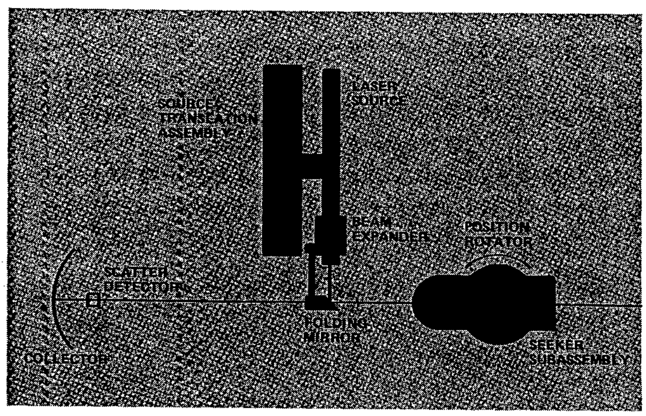


Figure 7

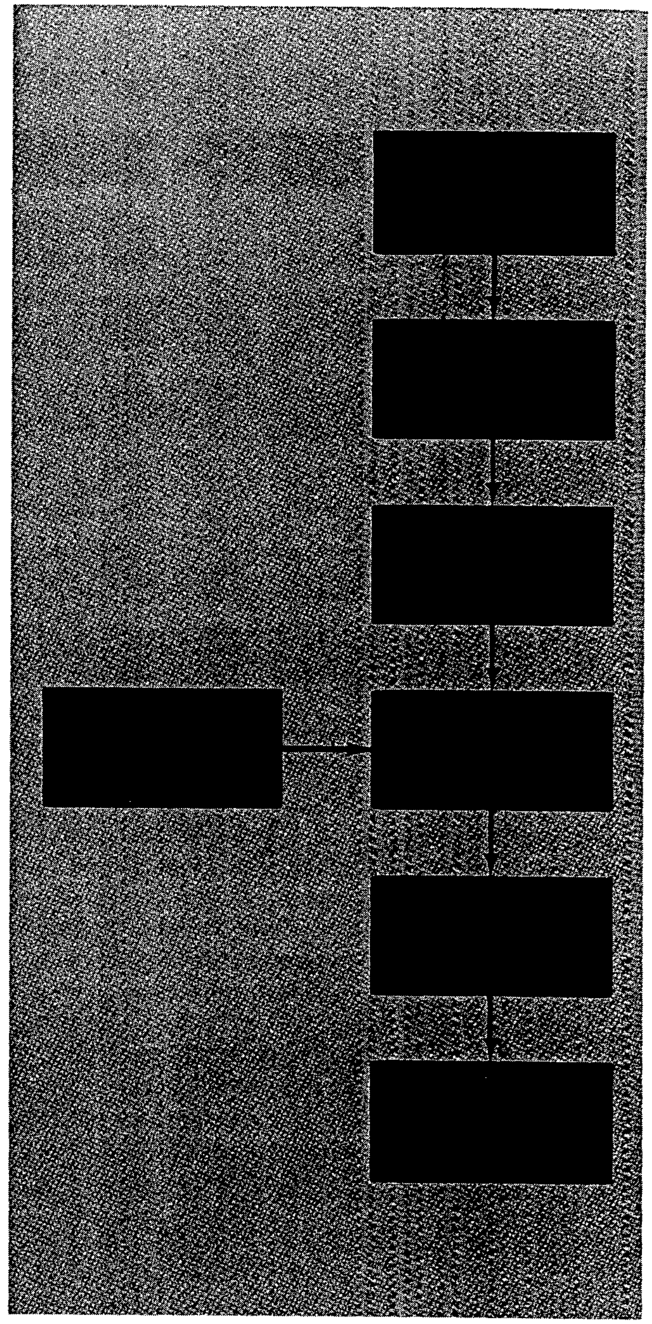


Figure 8

rotator. A laser source consisting of a helium-neon laser and beam expander is used to generate a laser beam approximately 1.6 cm in diameter. A folding mirror directs the beam onto the test component. The source assembly is mounted on two translators which are used to position the beam sequentially in a raster pattern over the entire area to be tested. An 8-inch collector mirror focuses the scattered radiation onto a silicon detector.

A diagram of the scatter measurement process is shown in Figure 8. The test assembly is positioned under computer control. The laser source is sequentially positioned for a raster scan of the component area. Detector measurements are collected and recorded. The entire data array is then used for processing the scatter profile of the test component. The data is further processed for display and storage.

The diameter of the iris opening is adjusted to test for a specific size or arrangement of defect. By scanning over the entire area of the input beam incident on the test system, a mapping of scattering centers can be made. Additional detailed analysis is accomplished for specific areas as needed by altering the iris diameter or the path scanned.

Two sources are provided to cover a wide spectral range from visible to infrared. A tungsten halogen lamp is used to provide a high intensity source from 0.4 to about 2.5 millimicrons. A blackbody source is provided to cover the spectral range in the IR from 1 to about 14 millimicrons. Bandpass filters allow bandwidth selection over a range of 0.4 to 14 millimicrons.

Programmable Controller Used

The programmable controller is permanently connected by cable to the mainframe. The basic system includes a Cromemco Microprocessor Based System. The system is capable of real-time branching based upon test results for a large array of tests. Input can be via keyboard or disk storage. Output can be by way of CRT display, printer, and disk storage. The disk storage is 512K bytes. This allows large programs, result-data keeping, and statistics and inventory control.

The software for the pilot facility is written using assembly language and FORTRAN programming. The devices chosen were selected based upon reasonable cost, ability to add features (peripherals, memory, etc.), ease of programming and low cost, reliability and convenience for using electronics interfaces (analog-to-digital converter packages, etc.).

The software was designed in a highly modular fashion which enabled easier development and maintenance. The basic modules are listed below and subsequently described in the remainder of this section.

- Pre-Test Software
  OTF test
  OTF calibration

- Test Sequence Software
  Translator reset
  Focus
  Peak search
  Focal length
  OTF
  Scatter
  180° rotation
  Off-axis position
  Inventory
  Statistical analysis.

Missile Seeker System

The seeker chosen for the pilot test facility is of the centroid tracking type. It operates in the near IR and is typically tested with a 1.06 mu laser source in a hardware-in-the-loop simulation system.

A series of benchmark tests in the simulation facility were made before the optical disassembly and testing began. The optical components and subassemblies of the seeker were organized for OTF and scatter determinations.

Adaptation of the test facility for specific optical tests required the solution of certain previously identified problems. The first was the initial reference alignment of the optical components or subsystems to be tested. For focus and OTF measurements, an initial axial and angular alignment to a reference on the component is necessary in order that physical parameters be determined relative to the component itself. All tests are then referred to these reference coordinates. By obtaining measurements in a scanning sequence, the actual parameter values can be determined.

One of the design features of the test facility is its ability to adapt easily to a variety of test component configurations. However, certain restrictions were imposed as a result of the physical properties of the test object. Constraints on the optical subassembly to be tested placed restrictions on the translation and scan movements allowed. The mounting of components to be tested is limited by the physical sizes and shapes for which the test assembly is designed. The optical resolution of the system is constrained by the optical quality of the collimator mirror and the angular resolution of the scanning rotation. Each of these parameters was chosen for optimization with the selected seeker. Each system parameter was analyzed quantitatively to determine its design limits and indicate the adaptability of other seekers or component types.

Test Results

The multielement lenses were tested broadboard over their entire spectral range. Focal lengths from 50-135 mm were used. F-numbers ranged from 4-5.6. A replicated aluminum mirror with a gold optical coating designed for a controid tracking missile seeker was tested at a variety of axis angles. A combination system using a mirror and dome assembly was then tested. Optical transfer function information relating to the dome was then derived. In addition to these tests, simulated defects were applied to the mirror entrance pupil such as opaque geometries and

scattering materials. Tests were then run to determine the effects on LSF and OTF. Scattering measurements were also performed on the seeker mirror.

HWIL Simulator Comparison

One of the major objectives of the test facility program is to provide a means for developing optical component standards related to a particular hardware system. To this end, tests were performed on the hardware-in-the-loop simulator. A series of tests were performed using simulated defects of both opaque and diffuse types. Comparison tests were then run on the optical component test system with a similar missile seeker mirror to obtain optical transfer function data for each case.

The missile was fitted with an adapter ring with a 6 inch aperture located approximately 0.25 inch from the seeker dome. The relative position of the adapter ring to the missile body was fixed, while the missile and adapter assembly were gimballed to simulate flight motion. Defect masks were then fitted to the adapter and "flown" in the simulator. The defect masks consist of an array of opaque or diffuse areas of various sizes and densities.

Four masks acquired and tracked well compared to the control mask with no defects. The average miss distance was less than 1 foot in all cases. Two masks, however, sufficiently degraded the optical performance to prevent tracking of the missile seeker during flight. Acquisition of the target was achieved in all cases.

To compare these simulator results to the actual optical performance of the system, line spread functions and optical transfer function data were generated. The same masks were used in combination with a seeker mirror. The optical transfer function for the four masks were very similar in their frequency and phase distribution. They agree well with the OTF obtained for the single mask with no defects. This is consistent with the simulator results, indicating close tracking capability. Two of the four masks, however, showed a clear degradation of the OTF, particularly in the low frequency range of amplitude. Because of the large area and small number of the defects on these masks, OTF measurements were also made off-center such that the center point of the mask was a distance of r/2 from the optical axis, where r is the mask radius. This position corresponds to the maximum contrast in mask position during the simulation. The OTF test results show a major shift in the amplitude response with distinct maximum and minimum. In addition, the phase also changes a full 180 degrees at each amplitude minima.

The test results show a clear correlation between the loss of tracking capability on the flight simulator and the degradation of the amplitude and phase characteristics of the optical transfer function. A few large defects were found to affect the OTF more than a large number of smaller defects. This is due to the nonuniform radial distribution characteristics of the large defect array as well as the nonsymmetrical distribution created as the mask is positioned off-center. The opaque and diffuse mask types yielded little difference in the results, indicating good compensation of the seeker to varying contrast levels.

Considerations for Full Scale Test Facility

One of the design features of the Automated Optical Test Facility is its ability to adapt easily to a variety of the test component configurations. However, certain restrictions are imposed as a result of the physical properties of the test object. Constraints on the optical subassembly to be tested have placed restrictions on the translation and scan movements allowed. The mounting of components to be tested is limited by the physical sizes and shapes for which the test assembly is designed. The optical resolution of the system is constrained by the optical quality of the collimator mirror and the angular resolution of the scanning rotation. Each of these parameters is chosen for optimization with the selected seeker. Since adaptability to other seekers or component types is desired, each system and performance parameter must be analyzed quantitatively to determine its design limits.

With the initial research and development of an automated optical component test facility accomplished, the question arises as to the cost of producing additional testing units. Presented in Table 1 are the individual categories which contribute to the cost of manufacturing an automated optical component test facility. It is assumed here that the time frame and costs are for fabrication only, which requires the largest capital investment. Additional design or programming modifications or installation costs have not been included.

Table 1

Hardware	$ 45 K
Technician (3 months @ $25/hr)	13 K
Engineer (1 month @ $35/hr)	6 K
Documentation	3 K
	$ 67 K

Also considered were the costs involved to upgrade an automated optical component test facility.

Etchant Isolation Critical

Semiflexible Thin Film Semiconductors

ROBERT L. BROWN is a General Engineer at the U.S. Army Missile Command in Huntsville, Alabama. His current projects involve creative direction of contractor engineers on projects such as the fully additive manufacture of printed wiring boards (Hughes), ultraviolet curing of conformal coatings for PC boards (Hughes), product cleanliness techniques for PC boards (Martin-Marietta), laser scan testing of PC boards (Chrysler), rigidflex assemblies (McDonnell-Douglas), and insertion of nonaxial lead devices in locaserts (Martin-Marietta), a recent approved success. A Registered Professional Engineer in Alabama and holder of a B.S. in Metallurgy (1958) from Alabama University, Mr. Brown holds six patents and is author of fifteen technical briefs which NASA rates as equivalencies to patents. He was the first recipient of the NASA "Noteworthy Contribution" award in 1970 for his many contributions to their technical utilization program, and patented several inventions that were used in production.

Widespread application in the electronics industry is an important feature of a new method of manufacturing thin film semiconductors that has been developed by the U.S. Army Missile Command. The process is not limited to only the particular semiconductor devices used to demonstrate the technique to industry, but can be used with many types of substrate and semiconductor materials. These can easily be isolated from the etchant reactants used in order to prevent damage to the item.

The new manufacturing technique is the outcome of an MM&T project conducted for MICOM by MicroElectronics Corporation of Auburn, Alabama. Initially planned as a two phase project involving the application of photolithographic methods for producing reproducible thin film transistors of highly reduced geometries, the project was widened in scope before its completion to include the development of manufacturing techniques for fabricating them on semiflexible substrates.

The first phase of the project consisted of a developmental effort devoted to the assessment, selection, and qualification of materials and processes suitable for fabrication of thin film transistors. The major milestones of this basic effort were to

- Design the manufacturing facility
- Specify and purchase equipment
- Receive and install equipment
- Develop the initial manufacturing procedure and processes
- Verify the procedures
- Document the progress.

This basic effort extended over a twelve month interval.

NOTE: This manufacturing technology project that was conducted by MicroElectronics Corporation was funded by the U. S. Army Missile Command under the overall direction of the U. S. Army Directorate for Manufacturing Technology, DARCOM. The MICOM Point of Contact for more information is Robert L. Brown (205)876-5879.

The option effort was a continuation of the initial manufacturing methods and technology of the basic effort. The major milestones were related to the

- Solution of identified problems
- Establishment of design criteria
- Manufacture of demonstration devices
- Cost analysis
- Industry demonstration.

This option effort occurred over a twelve month interval.

An addition to the original scope of the project occurred in the middle of the option phase. This effort required the manufacture of thin film transistors on two different substrates to establish the manufacturing technology of thin film transistors on semiflexible substrates.

Results Summarized

The project ultimately determined that

- Manufacturing methods/technology were developed to build thin film transistors with an improved metal masking technique. The critical source-drain spacing of this technique is defined photolithographically, while the semiconductor, insulator, and gate metallization are defined by metal masks.
- The manufacturing methods and technology was developed to build thin film transistors with an all photolithographic masking and etch technique.
- The ease of manufacture for the improved metal masking and the photolithographic methods were demonstrated using production techniques and production equipment.
- The manufacturing methods and technology for photolithographically produced transistors can be accomplished using equipment common to the semiconductor industry. No special modifications to normal equipment is necessary.
- The enhanced producibility due to reduced manufacturing steps and also the low temperature of the process results in a low cost, high yield manufacturing method.
- Thin film transistors can demonstrate significant levels of strain sensitivity.

Versatility of Properties

The unique properties of thin film transistors provide for a wide range of applications. The transistor characteristics typical of present monolithic device technology can be implemented with thin film transistors. The thin film approach provides a means of constructing transistors on any insulating substrate that will withstand the temperature and chemical environments of processing. The applications in such areas as sensors and displays are an excellent use of the thin film transistor properties. The fabrication of transistors over large flat areas produces a display with transistors for switching at the picture elements. This technology along with thin film electroluminescence techniques can result in flat panel displays of unique properties for applications in military battlefield, cockpit, and tank control displays. The light and strain sensitivity of thin film transistors makes applications in image and transducer technology an excellent area. The use of these sensors and transducers to detect light and measure pressure, force, or acceleration are possible implementation applications.

Typical generic applications which will use these devices include guidance and control sections of missiles and projectiles, aircraft and ship control systems, and field station information and control equipment. The basic properties of thin film transistors also make it possible to replace standard transistors with thin film transistors. The applications, therefore, become very broad with regard to their use.

Design Aspects

The thin film transistor functions as a metal oxide semiconductor (MOS) device. The three terminals of the device are termed the source, drain, and the gate. The material evaluated and used throughout this manufacturing methods and technology study was cadmium selenide, which as deposited forms an n-type material (majority carriers, electrons). The transistors operate as an enhancement mode device. The current flowing from the source to the drain was enhanced by an application of positive voltage on the gate.

The design aspects relate to the processing considerations necessary for the electrical performance of a device. The parameters of transconductance(the change in drain current as a function of gate voltage), operating voltage, and current are key performance variables. The channel length, the width-to-length ratio, the semiconductor and insulator thicknesses, the effective mobillity, and the gate capacitance are controlled by the processing. Figure 1 shows normalized thin film transistor characteristics.

Physical Effects On Performance

An important correlation must be made between the processing of the device and the actual characteristics obtained. The thickness of the semiconductor, the annealing time and temperature of the devices, and the step coverage of the particular layout all can influence the operation of the transistor. The most critical design aspect that is encountered is the smooth transition from one interface and layer to another. The step coverage of the source drain makes deposition of the semiconductor difficult. Accurate thickness control of the gate insulator is also necessary to ensure adequate breakdown voltages. The effective mobilities determined from actual device operation are

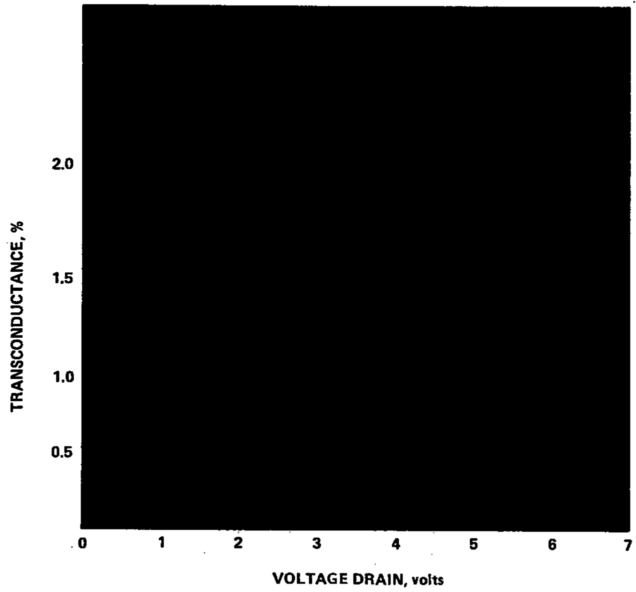


Figure 1

typically 30 cm^2/V-sec. The photolithographic technique allows channel lengths of down to four microns with aspect ratios of 800 as a typical demonstration device. The gate oxide thicknesses can vary from 200 to 1000A.

Third Phase Added

The primary objective of this manufacturing methods and technology effort was establishment of improved design and processing techniques for the manufacture of thin film transistors.

The basic effort was directed at the selection of the equipment, processes, and materials. The objective of this task was the initial planning and evaluation of the proper approach to the manufacture of thin film transistors. A major milestone to be accomplished was the development of a design for a computer controlled manufacturing facility for evaporated thin film transistors. Following the design effort, the objective of developing an automated system including the control of processes, materials, deposition conditions, and masking was to be accomplished. The basic effort also included an objective of developing interconnection, crossover, resistor and capacitor procedures, and parameters. The final objective of the basic effort was the verification of the complete system by development of a normal operating procedure.

The option task had as a central objective the firm establishment of the manufacturing method. The solution of problems and inconsistencies in device performance was a major objective of this task. Important correlations between the device characteristics and processing parameters were established. The option task also included completion of all the documentation of the equipment used to manufacture the transistors. The design criteria for the manufacture of the devices and the corresponding performance was to be completed in the option task. The final objective of the option task was to perform a cost analysis and an industry wide manufacturing process demo.

The addition to the scope of the option task included a characterization of thin film transistors on flexible substrates. The strain sensitivity evaluation of two sets of 100 small signal transistors on semiflexible substrates was a major task objective. The correlation of process parameters to this strain sensitivity was also a significant portion of the effort. The manufacture of thin film transistors on alternate substrates of various oxides was included as an objective of the task.

BASIC EFFORT

Equipment Selection

The basic equipment can be described as being composed of four major items. They are (1) the vacuum system, (2) the sources, (3) the process controller, and (4) the computer. The selection of the equipment for the manufacture of thin film transistors in a computer controlled system is a complex issue, with the equipment selected highly dependent upon the specific process used. The interaction of the equipment is a key element, with the utmost care necessary when the interface compatibility is considered.

Vacuum System. A complete review of available vacuum system suppliers was performed to determine the most applicable system configuration. The requirements placed upon this program with regard to a manufacturing methods and technology effort made small laboratory vacuum systems unacceptable. The attainment of vacuums in the 1×10^{-7} to 1×10^{-8} torr range was determined to be sufficient for the manufacture of thin film transistors. This was due to earlier research and development activity at Auburn University and elsewhere that resulted in the construction of thin film transistors with an oil based diffusion system.

The ultrahigh-vacuum systems with pumping modules other than oil diffusion systems were eliminated early in the evaluation effort due to their additional expense, and the confidence that devices would be fabricated with an oil based system.

The use of a rather large vacuum chamber so as to perform multiple depositions using several sources and mask changing mechanisms required careful evaluation during equipment selection.

Sources. The evaporation source for the material was evaluated with regard to the process and the vacuum system selected. From earlier published data and research work performed at Auburn University, it was determined that several resistive sources and a multiple hearth electron beam gun should be selected.

The selection of the electron beam gun and its associated power supply was performed with due consideration of the vacuum equipment, fixturing, and the fabrication processes. An electron beam gun with a minimum of four pockets—with each well or pocket having a volume of 30 cubic centimeters—was required. Two suppliers were determined to have equipment with adequate performance and maintenance history. The use of the deposition con-

troller also added to the selection criteria for the electron beam gun.

The resistive sources were of the filament type of design. The resistive source for the semiconductor was of the tantalum boat design, which allowed for the complete evaporation of the material without condensation on lower temperature locations of the source. The vacuum system was equipped with a 2.5KVA power supply with 5, 10, 20, and 50 volt taps. This power, which was connected to the filament or boat, was controlled by a 0-10 volt analog voltage. The deposition controls provided a signal that controlled the power to the resistive source with this 0-10 volt signal.

Deposition Controller. The control of the material thickness parameter is an excellent means of controlling the properties of a thin film material. The change in thickness with respect to time will provide the deposition rate. This deposition rate is an important property which is directly related to film nucleation and growth and therefore the electrical and mechanical properties. The monitoring of thickness and its corresponding control is performed by several different techniques. The change in conductivity or light absorption has been used to produce information on film thickness. One of the most effective means of determining thickness is the change in a crystal's oscillating frequency as material is deposited on its surface.

Deposition controllers using thickness information from an oscillating quartz crystal to determine deposition rate information are one of the most reliable and automated types. The features provided in such a controller allow for the control of temperature and time dependent power functions and rates of deposition. An evaluation of commercially available controllers indicated units that were the most advanced and compatible with an overall host computer. The computer selected is a microprocessor based system that has a well structured computer language feature. In addition, the access of up to 23 input and 23 output lines to control additional tooling or derive data as to the deposition in progress is available. A distributed system is used to control and monitor the deposition while a central computer can be used to decide alternate paths or derive and signal critical process changes. The system also can operate under an established program as defined in the microprocessor and thus not require the extensive software development typical of many computer controlled facilities.

Computer. The evaluation of a compatible computer facility with the proper configuration of input and output hardware, CPU, disk, and memory was performed to a large extent with the aid of Dr. Victor Nelson, Head of the Computer Laboratory of the Electrical Engineering Department, Auburn University, Dr. Nelson recommended and subsequent evaluations confirmed the suitable system for the computer controlled function of this manufacturing methods and technology effort. The computer system would be configured with a video terminal and keyboard for I/O along with a 30M byte disk drive and 96K of memory. With this selection of computer hardware, the communication between the computer and the deposition controller could be performed via serial interface. The only restriction on the interface port was that it must support the standard "handshake" signals of

DSR—(data set ready)—from controller to host computer to indicate readiness to receive data.

DTR—(data terminal ready)—from host to controller to indicate readiness of host to receive data.

The development of the software to control the deposition system and all of the associated support and tooling was a major task of the option phase of the total program.

System Design. The overall system configuration is shown in Figure 2. The computer can maintain control of all functions

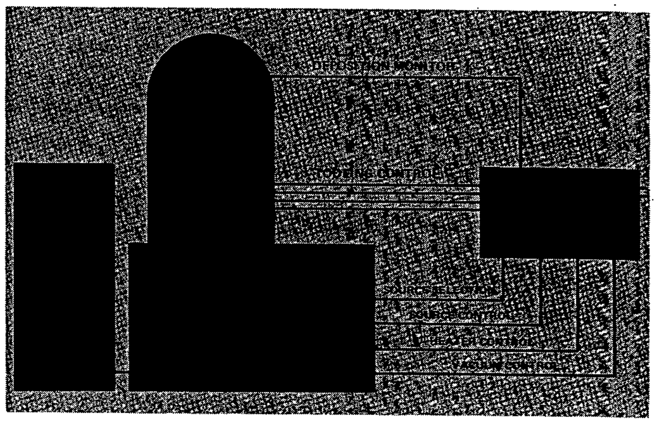


Figure 2

while critical processes are directly controlled by the deposition controller. This system was considered to be the most effective for the MM&T effort due to the reproducible and economical tradeoffs possible. The equipment is standard hardware, which should facilitate the technology transfer process. The computer control will provide decision options to be exercised and, therefore, increase the yield of the complex multistep process used in thin film transistors.

Tooling. The use of metal masks as stated in an earlier section of this report requires careful design and system integration to insure proper manufacture of thin film transistors. The tooling for this effort uses bimetal masks manufactured to an accuracy of 50 millionths of an inch. The metal masks have openings that provide an exact shadowed pattern on the surface to be deposited.

A key feature of the project was the manufacturing method developed during the basic effort which resulted in elimination of the total metal mask tooling concept. A complete photolithographic process was developed which provided a means of manufacturing thin film transistors, with alignments and exposure accomplished using a standard integrated circuit aligner. The productivity and manufacturing simplicity associated with the complete photolithographic process were a result of an effort to optimize the manufacturing techniques. The finalized construction of a computer operated metal mask changer approach was prioritized below the development of a more manufacturable photolithographic method. Over 20,000 metal masked thin film transistors were manufactured and their performance evaluated.

The metal mask fabricated thin film transistors thus were built on noncomputer automated tooling, but using the process steps and tools that would have been utilized if the automated mask changer was completed. The tooling for the deposition of non-patterned films to be used with the photolithographic manufacturing process was accomplished in the vacuum system by using a planetary substrate holder. The planetary revolved about the sources and rotated on a water cooled ring. The drive power for the planetary was accomplished by the use of a variable speed motor with a feedthrough in the top of the bell jar.

System Integration. For the interconnection of the critical equipment, the vacuum system, the deposition controller, and the computer, system integration is related to the functions that occur within the vacuum chamber. The data from the crystal oscillator is supplied to the deposition controller by a coax cable. The control of each source of deposited material can be selected from the deposition controller according to a specified algorithm. The control of the source power from 0-100% is also a significant feature of the system. The setting of temperature and the signal to start or stop the vacuum pumping action is via the deposition controller. The safety interlocks that insure cooling water flow and the proper pressure in the system are also part of the integrated manufacturing system.

In the metal masking design, the tooling required to hold the substrate and the metal mask are aligned to each other with tapered alignment pins. The substrate and the metal mask are prealigned to these pins to insure accurate manufacture of thin film transistors. A carousel rotates the substrate and the mask holder into approximate alignment. The mating assembly is pushed together to achieve final alignment of the substrate to the mask.

Fabrication Process. The manufacture of thin film transistors has been accomplished in a number of ways since the work of Weimer. Two different fabrication processes for thin film transistors are identified as the metal masking process and the photolithographic process. Typical metal masking techniques in the past have relied on the use of metal masks to define the source drain spacing. This technique therefore allowed the definition of all the transistor elements within the vacuum system with one pumpdown. The metal masking technique described in this report uses an innovation in the earlier process by defining the source drain spacing photolithographically and, therefore, providing a more accurate control of the critical spacing. The use of the photolithographically defined spacing provided for a channel length down to four microns, with seven microns being the typical high volume design standard.

With the results of the photolithographically defined source drain spacing, additional work was performed to define the entire thin film transistor photolithographically and thereby eliminate all metal masks from the process. The topology design and material cross section of the device had to be changed to accommodate the new process, but accurate seven micron channel lengths with a length to width ratio of over 800 to 1 were possible.

Material Selection. The materials for the manufacture of thin film transistors were a very important design consideration. Although semiconductor devices with cadmium sulfide have been produced, the sensitivity to the processing parameters of substrate temperature and source temperaure made evaluations with cadmium selenide more reproducible and manufacturable. The manufacture of thin film transistors made from cadmium telluride as well as indium antimonide have been demonstrated; however, the hazardous nature of the tellurium appeared to outweigh the performance characteristics for a manufacturing method.

The contact to the semiconductor was an important element in the selection of material. After an evaluation of the typically used systems and the results of research in this field which has related the degradation with time of thin film transistors to diffusion of the contracts, chrome was selected. The ohmic contact of chrome to cadmium selenide provides a stable controlled transistor if proper care is used to avoid chromium oxide and excessive internal stress.

The use of an insulator material that can be purchased with high purity and deposited to provide a high dielectric strength was necessary. The use of silicon monoxide, which is easily evaporated and readily available, was evaluated along with aluminum oxide. The aluminum oxide (sapphire) provided the best quality gate insulator for the thin film transistor.

The use of aluminum as a bonding and interconnection metallization was selected due to the ease of evaporation, good ohmic properties, and the economical advantages over gold. Improved metallization configurations using sloped etching made contact with aluminum and excellent process parameter. Another processing advantage of aluminum is the activation of chromium etching processes due to the electronegativity difference provided by the aluminum to chromium bimetal couple.

Metal Masking Process. The transistors fabricated using the metal masking process used a structure that provided for the source and drain on the lower layer of the device. The structure then had the cadmium selenide, the aluminum oxide, and the final gate metallization deposited through metal masks. Figures 3 and 4 illustrate the sequence of processing steps and a cross section of the device.

The first step in the fabrication process is the cleaning of the substrate. Following the cleaning process, the source drain metallization is deposited. The substrates are placed in the vacuum system and pumped down to a vacuum of 1×10^7 torr, with the substrates heated to a temperature of 100 C. The aluminum oxide is conditioned with the shutter closed so as to form a pool of liquid material in the center of a sapphire crystal. The deposition of the aluminum oxide substrate barrier occurs when the shutter is opened. The deposition rate of seven angstroms a second is used to deposit a total thickness of 1000 angstroms of material. Following the deposition of the substrate barrier material, the chromium for the source drain metallization is deposited.

The chromium source is rotated into position in the electron beam gun and the chrome is deposited and defined according to the MEC process.

The substrate is aligned to the metal mask for the cadmium selenide deposition. The MEC process describes this semiconductor deposition.

Following the cadmium selenide deposition, the metal mask for the gate insulator is positioned and the gate deposition is performed. The MEC process describes this semiconductor deposition. Following the gate insulator deposition, the metal mask for the gate metallization is positioned and the gate deposition is performed. The MEC process also describes this deposition.

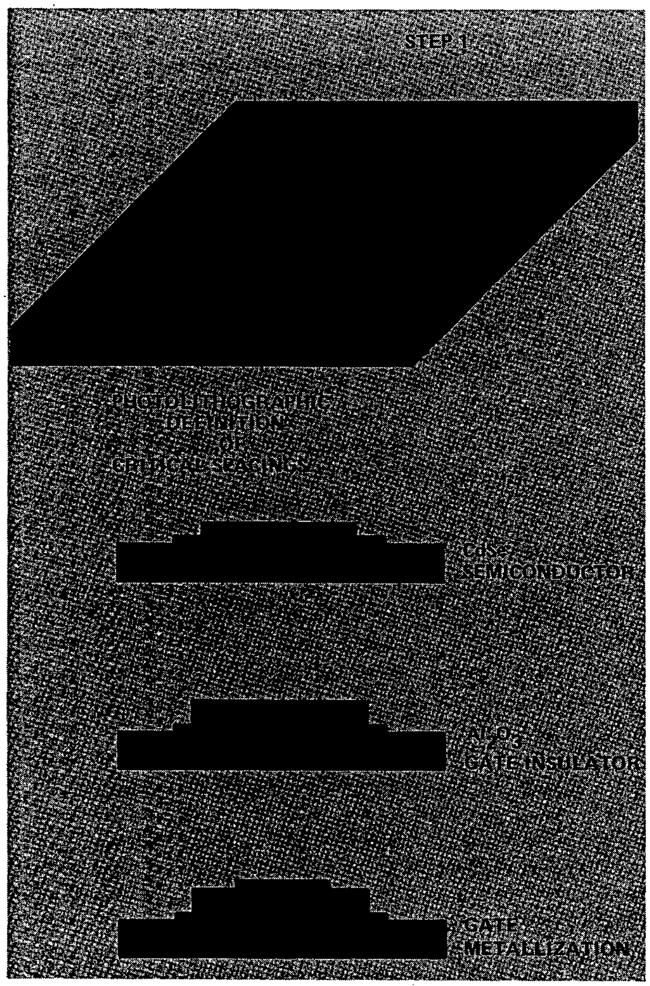


Figure 3

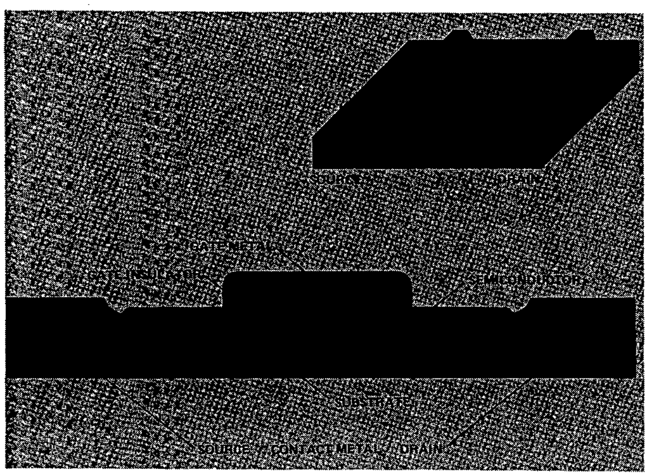


Figure 4

Figure 5 shows the design of a typical thin film transistor metal mask set. The design of the source and drain which were discussed in the earlier explanation of the metal mask approach results in a photolithographically defined chromium metal pattern. The metal mask for the semiconductor is aligned to the source drain metal. The final stage of Figure 2 shows a composite drawing of all the layers in alignment.

Photolithographic Process. The transistor fabricated using the photolithographic process uses a structure that provides for a metal gate on the substrate with the gate insulator semiconductor and the source drain metallization as the top layers of the device. Following the definition of the gate metallization as shown by the gate mask of Figure 6, the substrate is placed back in the chamber and the film of insulator, semiconductor, and contact metal are deposited onto the substrate.

OPTION TASK

In the option task of the effort, the routine manufacturability of the materials and processes of the basic effort was established. The key elements of the option task were the definition of the design aspects of thin film transistors, the proof of the manufacturing method by demonstration devices, and an evaluation of the cost of manufacture and an industry demonstration of the manufacturability of thin film transistors. The option task was initiated at the completion of the basic effort.

Design Aspects. The thin film transistor functions as a metal-oxide-semiconductor (MOS) device. The three terminals of the device are termed the source, drain, and the gate. The material evaluated and used throughout the manufacturing methods and technology study was cadmium selenide, which as deposited forms an n-type material (majority carriers, electrons). The transistors operated as an enhancement mode device. The current flowing from the source to the drain was enhanced by an application of positive voltage on the gate.

The design aspects relate to the processing considerations necessary for the electrical performance of a device. The parameters of transconductance, operating voltage, and current are key performance variables. The channel length, the width-to-length ratio, the semiconductor and insulator thicknesses, the effective mobility, and the gate capacitance are controlled by the processing.

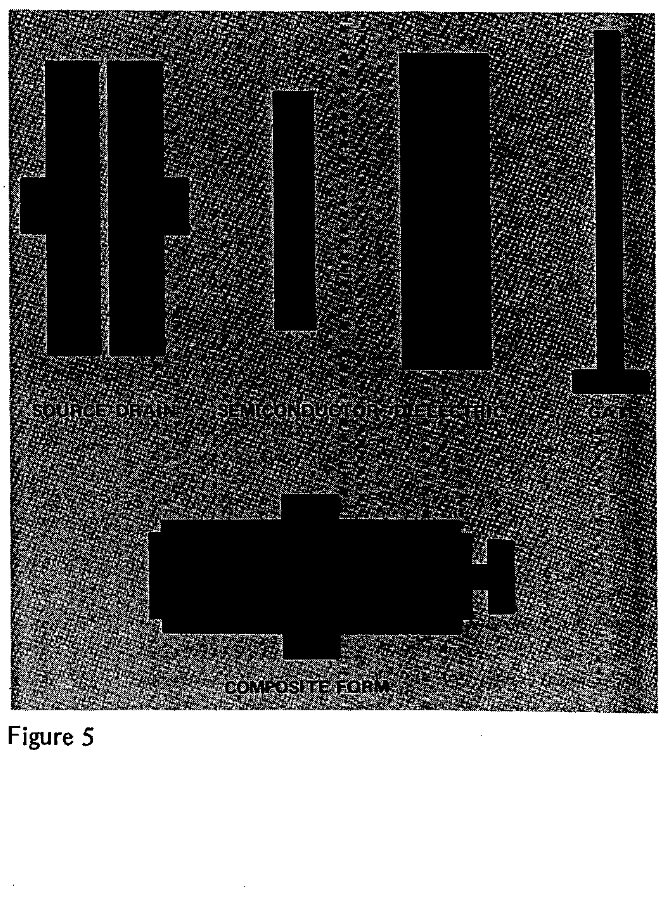


Figure 5

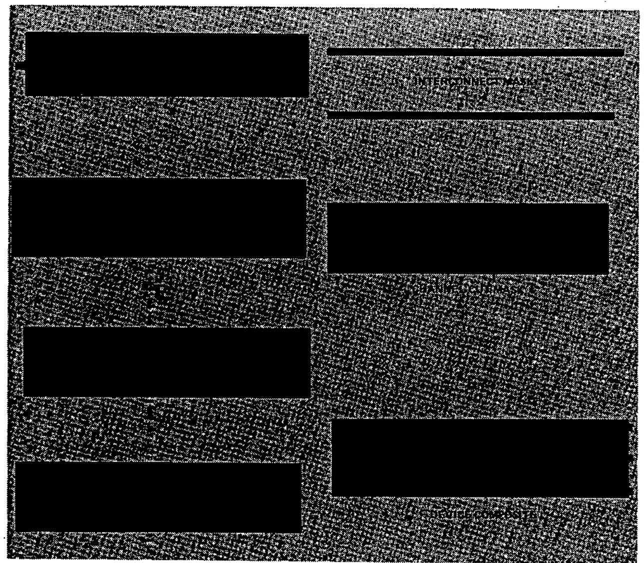


Figure 6

Demonstration Devices. The manufacture of devices that demonstrate performance according to the design aspects was a major task of the option effort. Extensive experimentation and process evaluation was performed to determine the proper processes for manufacture of the thin film transistors. The evaluation of process parameters such as temperature were an important element of the experimentation. The substrate temperature plays a very important role in the nucleation and growth kinetics of thin films. Evaluation of the combined effects of substrate temperature and deposition as related to substrate temperature provided an excellent insight into the combined effects of subsequent thermal histories on previously deposited films, especially semiconductors. The electron beam evaporation of aluminum oxide can generate significant levels of chamber heating, which was shown to be an important parameter in the manufacturing process.

The control of the deposition rate and total thickness of the gate insulator was an important processing variable, not only from the breakdown voltage aspects but also from the contact potential and thermal history considerations. The use of the proper combination of chamber pressure to insure minimal oxidation of the chromium—along with the substrate temperature and deposition rate of the cadmium selenide—were found to be critical to insure good ohmic contact.

The oxidation of the chromium beyond the specific limits of the process control resulted in low current carrying capability, with a corresponding distribution of voltage (source to drain)—a strong function of the path length. On some occasions, the current paths of the transistor could be seen as overheating-promoted diffusion and discoloration of the source-drain metallizations. The aspect of material purity cannot be overemphasized. The presence of even very small quantities of conductive material such as carbon, aluminum, or earlier depositions of cadmium selenide can severely alter the insulative properties of aluminum oxide. To insure consistent performance, the material for the insulator was examined and cleaned. The melt typically was formed in the center of a single crystal of the sapphire material.

Physical Design. The demonstration devices were fabricated with a variety of layouts. Two different transistors, each with a different source to drain spacing, were fabricated, a single channel device and an interdigitated metal mask fabricated structure. In this device, a common gate connection bar is provided when the source and drain metallizations are fabricated. This is necessary due to the structure that must be used when designing metal masks. A structure such as the multiple gates (which typically are long and narrow) must be supported on both ends of the mask for dimensional stability. This design is actually four transistors connected in parallel. The interdigitized structure allows for common connection of multiple sources and drains.

With the demonstration devices using the photolithographic fabrication technique, source-to-drain channel is produced by final etching of a uniform chromium deposition. This source-drain (channel) spacing was designed for maximum length by using the interdigitated design. The structure is an inverted gate, thus providing metallization under the bottom of the transistor. To insure that there would be no gate-to-semiconductor shorts around the outside edges of the structure, the insulator mask was designed to cover and extend beyond the gate metallization. A step in the fabrication process exists for gate contact. This provides electrical connection to the gate as well as the source and drain. The semiconductor contact metallization of chromium is enhanced by the use of aluminum to reduce resistance and thereby improve the current carrying capability of the transistors.

Electrical Performance. The transistors had a range of properties dependent to a large extent upon their processing history. There were two basic ranges of transconductance—the largest body of electrical data was derived from the transistors with transconductance of 10 to 300 micromhos. Shown in Figure 7 is the transistor characteristics device. The transconductance of this device is 100 micromhos.

The distribution of transconductance is shown in Figure 8 for one manufacturing lot. The transistor had well developed saturated characteristics. The gate breakdown voltage was greater than 25 volts. Maximum drain currents of up to 10 milliamperes

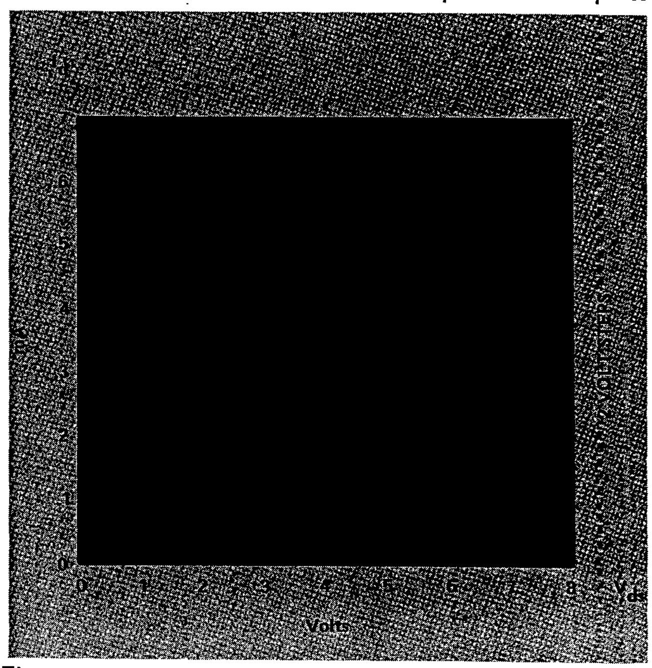


Figure 7

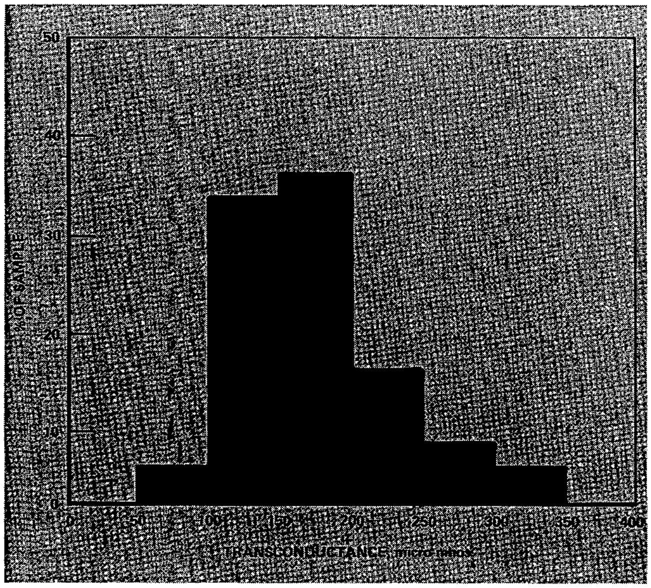


Figure 8

could be passed through the device before self heating and current crowding caused degradation in the device characteristics.

The evaluation of 50 lots of transistors fabricated using metal masks (giving a total of approximately 20,000 transistors) showed a range of transistor characteristics with nominal values of those shown in Figure 7. The breakdown voltages of the gate-to-source was 35 volts, except for situations where inadequate gate insulator thickness or step coverage resulted in leaky gates or low breakdown. An equivalent number of photolithographically defined transistors were fabricated. The increased aspect ratio of the source-drain channel provided higher gain devices.

Cost Analysis. The trend of constantly decreasing microelectronic manufacturing costs has been well established. The major elements in cost reduction (yield, lower packaging costs, higher volume) have continually improved to counterbalance increasing overhead. The analysis of manufacturing cost consists of direct material, direct labor, and manufacturing overhead. Factors which affect the cost of specific devices are the film deposition processes, substrate size, size of the devices, number of interconnections, package material, and yield throughout the production process. The variables that occur among competitors within the industry segment of interest are due to labor rates and utilization, equipment efficiencies, control of overhead, and degree of automation. Within the total manufacturing process, there are three major production costs: (1) substrate fabrication and die probe; (2) assembly; (3) final testing and finishing. This manufacturing methods and technology task was related to the manufacture of thin film transistors. The assembly and final testing and finishing of thin film transistors and conventional microelectronic devices are similar. Cost analysis therefore only considered the substrate fabrication and die probe as the manufacturing process for evaluation.

Transistor fabrication consists of various deposition, masking, and etching steps; cost variations among different circuits are due to the differing number of processing steps, tolerances allowed (especially in mask alignment), and metal interconnect layers. Yield losses in substrate fabrication are caused by breakage, masking misalignment, contamination, and operator error. Some of the substrates rejected at in-process inspection stations can be reworked to keep overall substrate yield between 60% and 80%.

With identical substrate costs, the die cost varies directly with the number of good electrical die per substrate, which is the result of the total available die per substrate multiplied by the probe yield. A 0.020 inch by 0.020 inch die size will result in 10,000 die per two inch by two inch substrate. The electrical probe yield experienced in this study was used in this cost analysis was 80%. Therefore, the final die (20x20 mils) per substrate were 8,000 die. The cost per die of the metal mask processed devices was 0.0053 dollar and the photolithographically defined transistors was 0.00394 dollar. As the production lots increase from the single substrate of this example to production lots of 10 and 100, the reduction in cost occurs due to the labor of Table 1. Therefore, a 50% reduction in labor for each production size of 10 and 100 will result in new substrate costs of $31.26 (10), $25.53 (100) for the metal mask fabricated devices and $21.85 (10), $17.01 (100) for the photolithographically process substrates. The price per die will, therefore, be reduced. Table 2 summarizes these calculations and is provided for comparison purposes only—exact amounts are a function of specific designs and manufacturing methods.

	Metal Mask	Photolithographic
1. Starting Material 2x2 glass	$ 0.60	$ 0.60
2. Masks	8.50	2.00
3. Chemicals, D.I. H_2O, Gases	2.75	2.75
4. Labor (U.S.) $6.50 average at 200% overhead	19.50	16.50
5. Equipment Depreciation (5 years)	5.00	5.00
	$36.35	$26.85
Average cost due to substrate processing yield	6.36	4.70
TOTAL	$42.71	$31.55

Table 1

Die Quantity	Metal mask Technique	Photolithographic Technique
10,000	0.533	0.394
100,000	0.391	0.273
1,000,000	0.319	0.213

NOTE: This table is provided for comparison purposes only—exact amounts are a function of specific designs and manufacturing methods.

Table 2

MODIFICATION TASK

The results of the option task indicated that additional effort in the manufacture of thin film transistors should be directed at the investigation of the strain sensitivity aspects. Published

reports by R. Muller showed that thin film transistors could exhibit an additional gate effect when the transistor is strained. The transistor demonstration devices of this project were fabricated using the metal masking process; the use of a special metallization interconnecting pattern made electrical probing during strain possible. Devices with source drain spacings which were parallel to the strain were probed as well as film transistors that were perpendicular to the strain.

Electrical Performance. The strain sensitivity of the thin film transistors was evaluated by examining the change in drain current as a function of strain. The test tool shown in Figure 9 was used to produce a given deflection in the substrate. The deflection was correlated to the strain using the standard equation for beam deflection. Shown in Figures 10 and 11 are the results of the strain versus drain current experiments.

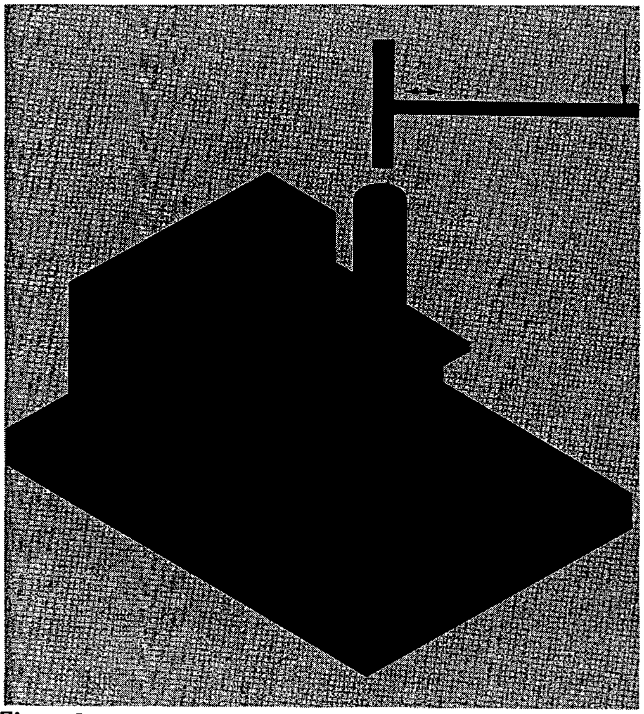


Figure 9

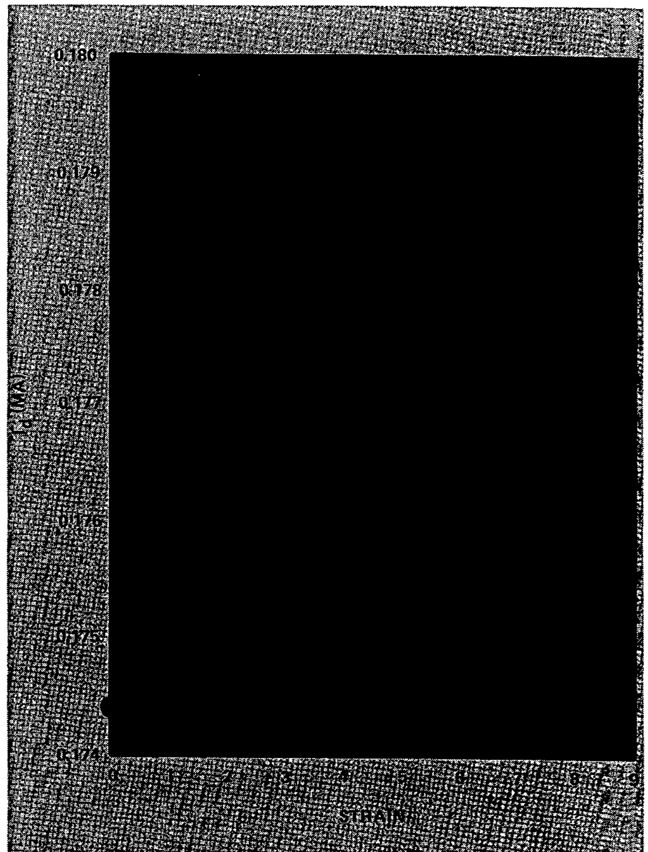


Figure 10

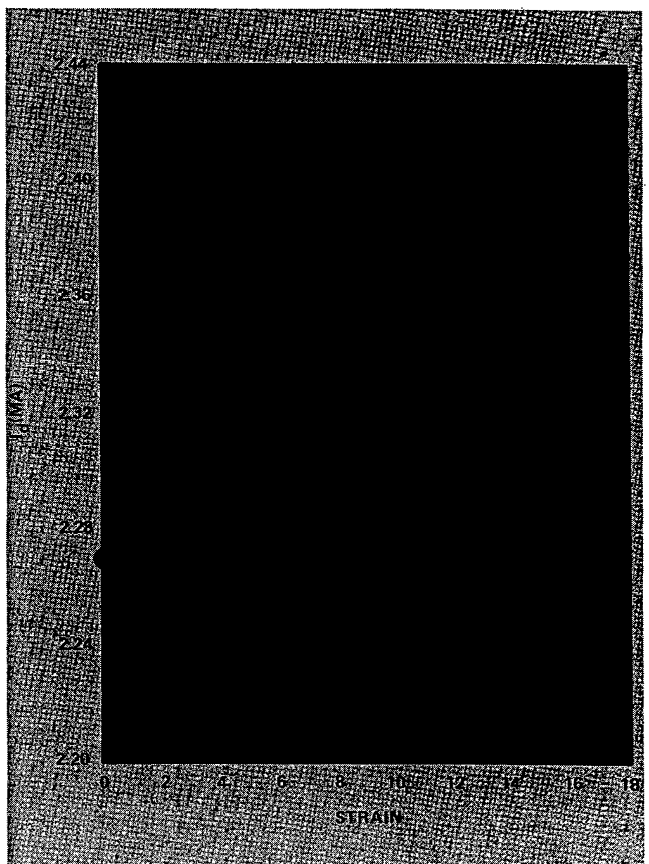


Figure 11

More Versatile and Reliable But Smaller

Transistors have made possible electronic systems of great complexity which perform functions such as communications, control, data processing, and signal processing. The functions have continued to increase in complexity while the space available for them has generally decreased. The applications, especially in the military, have been a forcing function to require ever increasing complexity and decreased size and weight along with reliability. This article has considered the manufacturing methods and technology of thin film transistors which enable the manufacture of a transistor or similarly a circuit of transistors on any type of insulating substrate.

The thin film transistor described is an insulated gate field-effect transistor in which the current is modulated by the same principle as in silicon MOS transistor. The differences are basically in the properties of the materials, the thin film and polycrystalline nature of the semiconductor, the modes of conduction, and the oxide semiconductor interface fabrication.

Positive Advance Mode

The unique manufacturing method of this project was the application of photolithographic methods for reduced geometries and ease of manufacturability. Manufacturing methods and technology efforts that have been funded in the past used metal shadow masks for the definition of the films. The use of shadow masks required carefully constructed mechanical tooling configurations to insure the proper sequence of alignments and material depositions. Here, photolithographic techniques were developed to define the critical source-drain spacing and also (in an alternate manufacturing method) the complete thin film transistor. The manufacturing method using photoresist and visual alignment results in better device characteristics with a more manufacturable method.

Recent trends requiring lightweight, compact electronic systems have led to miniaturization with unique packaging configurations. To achieve the required high-density electronic packaging with design performance, the development of thin film transistors has been identified as an important element. The manufacture of thin film transistors on substrates of many different configurations can provide a multitude of alternate packaging techniques. The use of insulating substrates that do not function as a circuit element, but simply provide mechanical support, therefore can provide low cost manufacturing solutions to the single crystal silicon substrates in common use today. The special properties of glass as both a substrate and a display medium is a typical application of thin film transistors for flat panel display technology. To increase the miniaturization and manufacturability of electronic equipment and produce unique designs and more functional systems, the United States Army Missile Command has funded this manufacturing methods and technology program for thin film transistors.

More Advances Possible

The results of the project have demonstrated improved manufacturing methods and technology for the fabrication of thin film transistors using metal masking technique as well as the photolithographic technique. The theoretical gain possible is much greater than the realized values, due in large part to imperfections in the polycrystalline nature of the semiconductor. An application of more advanced techniques of semiconductor technology, such as ion implantation and plasma assisted vapor depositions and etching could be applied to the manufacturing methods developed. Improved control of polycrystalline semiconductors used in the manufacture of thin film transistors would improve their characteristics.

Tests have been conducted of the class of transistors manufactured by this process; these tests point up some highly significant properties of the items: (1) the transistors function well at liquid nitrogen temperatures; (2) they also will operate for a limited time (20 min) at 300 degrees Centigrade; (3) they exhibit complete immunity to moisture damage—complete immersion for extended periods of time will not lessen their performance after drying.

The top voltage for which they've been designed to date is 1000 V, but higher voltages of operation are simply a matter of design.

Editor's Note: Readers may obtain more information by acquiring a copy of U. S. Patent No. 4,398,340 assigned to R. L. Brown—a generalized method of inexpensive manufacture of semiflexible thin film transistors.

Brief Status Reports

Project 3708. Coated Fabric Collapsible Fuel Tank Program. Circular seamless test and evaluation program initiated at YPG on 2 prototype seamless tanks. One tank filled with fuel/H_2O mixture and the other only H_2O. After 6 months, both tanks were in excellent condition with no signs of deterioration of the coated fabrics. For more information, contact K. K. Harns, BRDE, (703) 664-5433.

Project 3717. High Temperature Turbine Nozzle for 10 KW Power Unit. Engine testing of ceramic nozzle assemblies was initiated. Fifty hours of operation was accumulated on the first nozzle assembly. For more information, contact J. Arnold, BRDE, (703) 664-5459.

Project 3743. Composite Spun Material Launching Beam for Bridges. Technical work has been completed. Project complete. Structural beam elemments have been produced using winding techniques. Methods for mass producing complex pin joints have been developed and demonstrated. The final technical report detailing the process has been prepared. For more information, contact R. Helmke, BRDE, (703) 664-5176.

Project 7200. Composite Engine Inlet Particle Separator. All technical work is completed. The final technical report is available. For more information, contact Bill Brand, AVRADCOM, (314) 263-3079.

Project 7241. Hot Isostatic Pressed Titanium Castings. Production of low cost blackhawk damper bracket using HIP and heat treated titanium investment casting. This bracket will be interchangeable with the present forged bracket. For more information, contact Bill Brand, AVRADCOM, (314) 263-3079.

Project 7286. High Quality Superalloy Powder Productiion For Turbine Components. Effort initiated with ingot processing by electron beam remelt. For more information, contact Bill Brand, AVRADCOM, (314) 263-3079.

Project 7300. Improved Low Cycle Fatigue Cast Rotors. Material screening testing complete and final proces selected. Casting vendor producing next lot of castings for material test evaluation and field engine testing. For more information, contact Bill Brand, AVRADCOM, (314) 263-3079.

Project 7351. Composite Shafting for Turbine Engines. A technical report presents the Phase 1 work accomplished. After a review of Phase 1 results, approval was granted to proceed with Phase 2. Fabrication of a full scale diameter, one-half length shaft was initiated. For more information, contact Bill Brand, AVRADCOM, (314) 263-3079.

Project 7412. Infrared Detector for Laser Warning Receiver. Confirmatory and pilot run samples indicate a yield from 30 to 70 percent. These INAS IR detectors will be used in the AN/AVR-2 program. Will build and test interdigitated IR detectors for AN/AVR-2 program. For more information, contact Bill Brand, AVRADCOM, (314) 263-3079.

Project 7415. MMT T700 Blisk Repair. GE has obtained 26 blisks. Welding operations have been defined. The heat treat cycle has been selected. Corrosion and high cycle fatigue test plans have been formulated. Design of tooling for weld and heat treat is complete and on order. For more information, contact Bill Brand, AVRADCOM, (314) 263-3079.

Project 3050. Epitaxy of III-V Semiconductor Photodetectors. RCA of Canada contracted thru Canadian Commercial Corp. to establish methods for making photodetector modules for AN-GAC-1 long haul and AN-TYC-39 local fiber optic communications systems. Liquid or vapor phase epitaxy of IN-GA-AS-P were used. For more information, contact Al Feddeler, CECOM, (201) 544-4926.

Project 3056. Electroluminescent Numeric Modules. Rockwell installed 18 in. and 24 in. thin film vacuum deposition chambers for electroluminescent numeric display modules. For more information, contact Al Feddeler, CECOM, (201) 544-4926.

Project 3073. Tactical Graphics Display Panel. GTE Corporation experienced row shorting problems in fabricating 10 x 12.5 inch thin

film electroluminescent display panels. Diagnostic tests are under way. Drive electronics almost complete and testing has begun. Pilot line producing 10 panels a day is goal. For more information, contact Al Feddeler, CECOM (201) 544-4926.

Project 3094. Communications Technology Techmod for JTIDS. Contracts awarded to Singer-Kearfoft and Rockwell-Collins to analyze their manufacturing operations to identify areas needing upgrading. Phase 2 will include establishing and demonstrating new capital equipment and techniques. For more information, contact Al Feddeler, CECOM, (201) 544-4926.

Project 9851. Tactical Miniature Crystal Oscillators. Bendix defined braxing, bonding, cleaning, outgassing, and sealing processes for 1 cu. in. TMXO. Vacuum analysis and a crystal temperature slew test station were completed. Test fixture construction has begun. Hybrid circuit fabrication has started. For more information, contact Al Feddeler, CECOM, (201) 544-4926.

Project 9938. Three Color Light Emitting Diode Display Unit. This effort is complete and final report is completed. For more information, contact Al Feddeler, CECOM, (201) 544-4926.

Project 1072. Multiple High Reliability/Low Volume LSI Manufacturing (CAM). Insouth Microsystems is developing processing blocks for manufacturing several circuit types utilizing several technologies. This includes obsolete circuits in isolated junction bipolar, dielectric isolated bipolar, metag gate CMOS and SI-gate CMOS. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 1073. Real Time Ultrasonic Imaging. The third program review was held. Although total integration of the prototype had not been completed, much of the system performed well. High quality imagery of flaws in the viper tube was demonstrated. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 1076. Automatic Recognition of Chips. Kulick and Soffa Industries is prototyping a small robot and a material handling system and pattern recognition equipment to identify and orient chips, place them on the proper pad on a substrate, and bond them. KES is demonstrating parts to industry. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 1088. Optimized Mandrel Fabrication and Utilization For Composite Motor Cases. A second motor case has been hydroburst. The burst pressure was 1740 psig, well above the minimum expected. The program is on hold status awaiting a case insulator from the elastomeric insulation MMT program. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 3139. Millimeter Seekers for Terminal Homing (TH). All elements of this contract are complete. Awaiting unclassified version of technical report. A special working group evaluating concept definition proposals for terminally guided warhead received the implementation plan for MLRS-TGW. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 3263. Printed Wiring Boards Utilizing Leadless Components. Hughes Fullerton found polyimide/kevlar circuit boards mounted on copper-invar-copper thermal plate best at thermal cycling. 84-lead ceramic chip carriers were vapor phase soldered to the boards. Corner joints were reinforced with rigid epoxy resin. For more information, contact Bobby Austin, MICOM, (205) 876-4197.

Project 3294. Production Processes for Rotary Roll Forming. Technical effort is complete. Final report draft is approved. For more information, contact Bobby Austin, MICOM, (205) 876-4197.

Project 3376. Testing of Electro-Optical Components and Subsystems. All technical work has been accomplished, final technical report draft has been received, modified and approved. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 3423. Low Cost/High Performance Carbon-Carbon Nozzles. Concept refinement and reproducibility testing have been completed. For more information,

contact Bobby Austin, MICOM, (205) 876-2147.

Project 3441. Application of High Energy Laser Manufacturing Processes. All work has been completed. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 3445. Precision Machining of Optical Components. A major component of the contouring machine tool controller was redesigned and fabricated. The machine was successfully repaired. Additional funds were requested to provide documentation and promote technology transfer. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 3449. Alternate Process for IRDI. Program plan reviewed. Literature review completed. Preliminary production plant design and cost estimates started. All required reports prepared and received. For more information, contact Bobby Austin, MICOM, (205) 876-2147.

Project 4575. Laser Welding Techniques for Military Vehicles. Production mock-up using M 1 turret ring casting to inner turret wall completed. Final report film and contract close-out targeted. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5014. Foundry Casting Processes Using Fluid Flow and Thermal Analyses. Contract with the University of Pittsburgh was amended to expand the geometric capabilities of the current procedures. Presentation of program results was made to foundry and tool design representatives for the foundries of Deere and CO and Rock Island arsenals. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5019. Storage Battery Low Maintenance. Prototype batteries from contractor have been delivered to YPG and CRTC for field vehicle tests. Satisfactory performance tests also began. Latter tests very good. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5024. Gear Die Design and Manufacturing Utilizing Computer Technology (CAM). The script for the movie on CAD/CAM of spiral beval gears has been prepared. Shooting is nearing completion. The report is available to all interested parties. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5045. Spall Suppressive Armor for Combat Vehicles (Phase II). An M113 with spall kit loaded with items of personal gear, rations, NBC gear and ammo was fired upon by 2 types of heat ammo. Results showed that the kit performed its function by reducing fragment spray and containing the stowed items. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5053. Fabrication Techniques for High Strength Structural Ceramics. Work to optimize material technology for monolithic ceramic and ceramic coated components. Initial materials passed rupture and toughness tests. AMMRC initiated work on ceramic composites. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5054. Laser Surface Hardened Combat Vehicle Components. Non-surface hardened T-142 and T-156 end connectors and center guides have been purchased. Components are being heat treated. Lab evaluation of laser heat treated components is in progress. Draft final report is being reviewed by the government. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5064. Light Weight Saddle Tank (Phase III). All requested government-owned material forwarded to contractor. Design of tank tooling and fittings finished. Wood mockup of final fuel tank configuration checked for fitting locations and installations. After passing test fuel tanks sent to 4 test sites. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5067. Plastic Battery Box. Final report distributed and validated economic analysis published. Test plan for in-house multi-temperature stress test on M809 box is in progress. Four M39 battery boxes ordered for YPG and installed on the 2.5 ton truck by contractor, AM general. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6350-2205. Holographic Inspection of Rotary Forged Preforms. The design effort for high resolution flow inspection system is 75 percent complete. Prototype electronic cards have been wirewrapped, tested, and debugged. The CVI 200X was recently delivered to RPI. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2225. 3D Shock/Vibration Test for Missile and Artillery Fuze Materials. The project has been successfully completed and a final report is being prepared. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2422. Inspect/Measure Method for Spherical Surfaced Components. The technical work has been completed. A technical report is being published. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2425. Optical Testing of Far Infrared Materials. Interferograms were made on 45 germanium optical blanks. The samples normally were three inches in diameter and one-half inch thick. The samples showed a mean variation in index variation. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2433. Automatic Universal High Voltage Power Supply Test Console. The electronic console has been completed and is being used in the manual mode to test ANVIS, AN/AVS-6 power supplies. The system operating program has been completed and at least 12 of 70 individual test sequences have been completed. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2444. Ultrasonic Testing of Roadwheels. This project has been completed. Distribution of the technical report is under way. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2446. Blacklight Video Inspection System. Additional funds to continue the work were made available. A purchase request for an off-the-shelf video system has been sent to procurement directorate. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2614. Temperature Compensated Voltage Controlled Crystal Oscillator Test Method. Testing for evaluating frequency stability of (TCVCXO) as crystal controlled crystal clocks in the DGM equipment was completed. A draft TR report has been submitted and evaluated. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2628. Standard Contaminant for Test Fuels. This effort has been completed and the final technical report, APG-MT-5759, has been published. This report contains the instructions in the use of polypropylene powders to check the efficiency of fuel filters. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2639. Roadwheel Seal Test Machine. Procurement of required purchase item is in progress. In-house fabrication of the machine is in progress. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2646. Piston Actuator Test. Assembly of the system is complete. The design has been frozen. The system is being calibrated at the present time. After calibration, 100 piston actuators will be tested and the final report written. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-3006. Acoustic Emission Monitoring/Control Straightening. The scope of this project has been expanded. Additional funds for engineering labor and small parts manufacture and acquisition have been requested. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 5071-14. Smoke Obscuration Test Procedures. The investigation has been completed and final report was approved. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-73. Integrated Test Data Acquisition. Three integration test networks employing optical fiber data links have been built. Two of these systems have been bench tested and have had limited field tests. A third prototype is being prepared for test. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-74. Smoke Sampling/Characterization. Tests have been initiated to eliminate the problem of mounted sampler movement on exposure to the explosive shock of the smoke round. Wind tunnel tests for sampling oil, diesel oil and IR obscurant were coordinated. Final report was submitted and approved. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-79. Environmental Issues Guide for Humid Tropic Testing. The basic matrix has been developed and coordinated with topographic labs. The program concept for entering and retrieving data is complete. For more information, contact John Gehrig, TECOM, (301) 278-2375.